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Geoscience and a Lunar Base

A Comprehensive Plan for Lunar Exploration

Proceedings of a workshop held at
the Lunar and Planetary Institute
Houston, Texas
August 25–26, 1988

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Geoscience and a Lunar Base

A Comprehensive Plan for Lunar Exploration

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PREFACE

This report was produced at the request of Dr. Michael B. Duke, Director of the Solar System Exploration Division of the NASA Johnson Space Center. At a meeting of the Lunar and Planetary Sample Team (LAPST), Dr. Duke (at the time also Science Director of the Office of Exploration, NASA Headquarters) suggested that future lunar geoscience activities had not been planned systematically and that geoscience goals for the lunar base program were not articulated well. LAPST is a panel that advises NASA on lunar sample allocations and also serves as an advocate for lunar science within the planetary science community. LAPST took it upon itself to organize some formal geoscience planning for a lunar base by creating a document that outlines the types of missions and activities that are needed to understand the Moon and its geologic history. The committee wrote a draft of the report between February and June, 1988, with the help of two other scientists (listed below) and then organized a workshop to gather the thoughts and opinions of a broad spectrum of lunar scientists on the science opportunities and technical challenges posed by a lunar base program. The **Workshop on Geoscience from a Lunar Base** was held August 25-26, 1988 at the Lunar and Planetary Institute in Houston, Texas. Participants (see below) divided into small working groups to discuss, expand, and revise the report's content. Additional revisions were made by LAPST members, workshop participants, and other lunar scientists during the following year. The editors would like to thank all participants in this effort for their work; however, we assume full responsibility for the accuracy and clarity of the final version of this report. We believe that this report is not only a valuable summary of the aspirations of our science, but a blueprint for the next generation's geologic exploration of another world.

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EXECUTIVE SUMMARY

The Moon is a fascinating place. It has a rich and diverse geological history that has yet to be read in detail, despite the success of the Apollo program and twenty years of study of the 385 kg of rock and dirt returned from the Moon. This is not surprising: the Earth has been studied intensely for over two centuries and we still regularly gain insight into its geologic history and how it works. The Moon contains resources to use in space as humans migrate into the Solar System; these resources have yet to be fully characterized. The Moon is the closest extraterrestrial body to Earth, and it will surely be the first to be occupied permanently. This report presents a comprehensive plan for the geologic exploration of the Moon.

Scientific importance of studying the Moon

The Moon plays a key role in planetary science, providing a unique window into Solar System history: its origin is intimately connected with that of Earth; its craters preserve a record of meteoroid fluxes through time, which may relate to extinctions of life on Earth; it preserves a detailed record of its early evolution. The Moon is an ideal body on which to study the processes that have shaped the other solid bodies in the Solar System, such as impact. The Moon is also the only extraterrestrial body from which we have samples from known locations, providing a much more quantitative understanding of its history. The lunar soil preserves a four-billion-year record of the Sun's history; in a sense the Moon is a solar telescope with a tape recorder. Finally, the Moon is the most accessible body in the Solar System, making its exploration easier to achieve.

The Apollo program provided an unprecedented leap in our understanding of the Moon. We discovered that it is an ancient body that formed when the Earth and other bodies formed, 4.5 billion years ago. The Moon is not primordial and undifferentiated. Instead, Apollo samples show that the Moon was substantially molten soon after it formed; most scientists believe it was surrounded by an ocean of magma that crystallized to form the original crust and mantle. The ancient crust was modified by subsequent igneous activity, during which a variety of magmas pooled in the crust and flowed across its surface. The youngest (3.8 to about 1.0 billion years old) lavas erupted onto the surface to create the dark-colored maria that decorate the Earth-facing side of the Moon. The Moon underwent a catastrophic early bombardment that ended about 3.85 billion years ago; this epoch was experienced by all the terrestrial planets, including Earth. Measurements of the magnetism of lunar rocks indicate that the Moon may have had an internally-generated magnetic field early in its history, suggesting the presence of a small metallic core. Seismic studies show that, at present, the Moon is solid to a depth of about 900 kilometers.

In spite of the great success of Apollo, unanswered questions about the Moon abound. We do not know with certainty how it formed and how its origin relates to that of the Earth. We do not know the details of its early igneous history--a key episode in the history of all the solid planets. Because we do not know the full compositional and age ranges of lunar volcanic rocks, we lack information about the mantle and thermal history of the Moon. We have scant information about the lunar interior or compositional variations in the crust. A magnetic field may have been generated inside the Moon early in its history, but we do not know for certain the size of the metallic core, or even if there is one; determining the size of the core will help determine how the ancient magnetic field was generated. The quantitative details of the bombardment history of the Moon are unknown. Our knowledge of the lunar atmosphere and its interaction with the solar wind is as tenuous as the atmosphere itself. These problems can be addressed by global surveys, reconnaissance sample-return missions, and detailed field studies from a lunar base.

The Moon is also an ideal platform for other types of scientific investigations. Its flimsy atmosphere, seismic stability and low radio-noise background on the far side make it ideal for astronomical observations. The thin lunar atmosphere allows observations of the solar wind plasma; an array of sensors on the Moon would lead to a better understanding of the processes that energize and transport plasmas. Study of the interaction of neutral gases released from lunar base facilities would shed light on problems as diverse as the origin of the Solar System to the transient behavior of comets.

The Moon is an excellent site for observations of both the present Earth and its intricate geologic history. Instruments on the Moon can view the land and oceans, the atmosphere, and the outer regions of the ionosphere. Unlike satellites at geosynchronous orbit that can view only one hemisphere, a lunar sensor array can view all locations on Earth each day, including polar regions. The regolith contains a four-billion-year record of the Sun's history; deciphering this record will improve our understanding of how the solar output varies with time and improve the basis of predictions of how it will vary in the future. Lunar craters can be dated to provide tests of the hypothesis that mass extinctions of life on Earth were caused by periodic increases in the impact rate on our planet.

Global surveys

Two major types of global studies of the Moon must be done. One is a polar-orbiting spacecraft that would map the Moon geochemically, mineralogically, and geophysically, such as Lunar Observer. This mission, slated by NASA to fly in the 1990s, will shed light on many unsolved problems, including constraints on lunar origin and the Moon's magmatic history. The other type of global study involves surface deployment of a network of geophysical instruments that would probe the lunar interior and monitor the Moon's atmosphere. These could be deployed by automated landers or roving vehicles, penetrators, or humans.

Reconnaissance missions

Automated landers could be sent to many sites on the Moon to collect and return samples for analysis on Earth. Each such mission would be designed to address a small number of specific questions (e.g., what is the age of the youngest volcanic rocks on the Moon?), so sampling strategies would be simple and relatively easy to automate. The spacecraft could be similar to Soviet Luna spacecraft, but with a more sophisticated sample collection system and greater return payloads. Ideal samples would be 1 kg of 1 - 4 cm rock fragments obtained by a rake, 200 g of bulk soil, and a core 1.5 m deep (about 900 g if the core is 2 cm in diameter).

Field work

Geological field work requires long-duration missions that will address complex questions and result in detailed characterization of sites studied. Capabilities for field work will expand with time. During the emplacement phase of a lunar base, most sampling would be confined to sites within a few tens of kilometers of the base; this could be expanded to about 100 km with the development of pressurized roving vehicles. Giant leaps in geologic exploration will come with the development of robotic field geologists teleoperated by geologists at the base or possibly, on Earth. Through telepresence, the operators of these robots will be electronically transported to a remote site, transforming a single base into a global base.

Scenarios for geoscience exploration

The sequencing of the missions described above is flexible, although accomplishing the Lunar Observer mission first would optimize the other operations. Reconnaissance and network science can begin before or after a lunar base is established. A modest amount of field work can begin near the base, but can ultimately take place anywhere on the Moon using roving vehicles carrying either human geologists or teleoperated robotic field geologists.

Required technological developments

The geoscience investigations described in this report will require solutions of some interesting technological problems. Besides technologies required for human habitation and transportation on the Moon and between it and Earth, some developments are unique to geoscience investigations. A new generation of geophysical instruments and their power supplies must be developed. Research is needed on how to deploy a geophysical network most effectively (soft landers, penetrators, or people) and on how to orient instruments once they are deployed. Specialized geophysical instruments, such as a geophone line, need to be developed for use by crews near a base. Automated soft-lander spacecraft must be developed for returning samples from reconnaissance missions. Tethers may be used on advanced orbital missions, where remote sensing instruments could be lowered close to the surface to obtain high spatial resolution. Automatic roving vehicles need to be designed to carry geophysical instruments and teleoperated robotic field geologists. Human transportation vehicles will also be needed; these should be pressurized for long traverses and unpressurized for use near the base. A number of sampling devices must be available, ranging from simple tools such as scoops and rakes to sophisticated equipment such as drill cores, capable of drilling to depths of a few meters in soil to a few hundred meters in rock. Finally, to convert a single base into a global base, the teleoperated robotic field geologist must be developed; this complex task requires continued research on telepresence (including eyesight and tactile feedback), mobility, communications, navigation, electronic subsystems, sampling tools, and power.

I. INTRODUCTION: THE SCIENTIFIC IMPORTANCE OF THE MOON

The Moon is a fascinating place. It has a rich and diverse geologic history that is yet to be read in detail, in spite of the success of the Apollo program and twenty years of study of the 385 kg of rock and soil Apollo astronauts returned. One should not be surprised that the details of the Moon's geologic history have not been deciphered. After all, the Earth has been studied intensely for over two centuries and we do not yet fully understand its geologic history or how it works. The purpose of this report is to develop a comprehensive plan for the geologic exploration of the Moon.

The Moon holds a central place in planetary science. There are several reasons for this:

First, it is the most accessible body in the solar system. It takes only two or three days to get to and there is almost always a launch window. To some extent, its near side can even be studied remotely from Earth's surface.

Second, it is a touchstone for the history of the Solar System. Though its origin is not known with certainty, it seems likely that it is intimately connected with Earth's origin. The Moon's craters record the flux of projectiles through time, which may relate to extinctions of life forms on Earth. Among the rocky planetary bodies such as Venus, Earth, and Mars, the Moon is relatively simple and has preserved a detailed record of its evolution.

Third, the Moon is the gateway to understanding the processes that shaped the other Earth-like bodies in the Solar System. For example, great impact basins are preserved on the Moon and can be studied in detail to understand the mechanics of their formation and their ages. As another example, the concept of the formation of primordial planetary crusts by planet-wide melting was developed from the study of lunar samples.

Fourth, the Moon is the only body other than Earth from which we have samples from known locations. Consequently, because samples of the lunar crust have been obtained and dated, the Moon serves as the basis for calibrating age estimates by crater counts on the surfaces of other bodies.

Fifth, because of our understanding of the Moon provided by the Apollo program, we are in a position to address fundamental problems in planetary science by asking detailed, sophisticated questions of the Moon, the answers to which can be provided by specific measurements.

Finally, the lunar surface contains a record of the Sun through time in the form of trapped solar wind particles and solar flare products. In essence, the Moon is a solar telescope with a tape recorder.

Besides these compelling reasons to understand the Moon's geologic history, geoscience will also provide valuable information about lunar resources. For a lunar base to become an integral part of space commerce, it must eventually be able to provide raw materials for use by industrial operations in space and on the Moon. Consequently, the search for and characterization of resources will be an important part of the exploration conducted from a base on the Moon.

Geoscience will be an essential ingredient of a lunar base program. This report develops a comprehensive plan of geologic exploration to be conducted before, during, and after a base is established on the Moon. It describes unsolved problems in lunar science, explains what kinds of research need to be done to solve these problems, and the techniques and technology needed to carry out this research.

II. UNSOLVED PROBLEMS IN LUNAR SCIENCE

After years of study, we possess a broad outline of the Moon's origin and geologic evolution, but our understanding remains inchoate. Unanswered questions range from those of global and fundamental importance to those of more specialized importance. This chapter outlines some of the unsolved problems of lunar science.

UNANSWERED QUESTIONS

We could easily list a hundred specific questions that must be answered if we are to understand fully the origin and evolution of the Moon. Instead, we here outline the types of unsolved problems of lunar science to give readers an idea of the scale of scientific inquiry we are dealing with.

How did the Moon form?

This most general of questions has been asked for centuries. The idea that the Moon formed as a result of an impact into the early Earth by a planetesimal the size of Mars has recently become the most favored among hypotheses of lunar origin, but testing it requires a more precise knowledge of the Moon's bulk composition and initial thermal state. In turn, learning more about the Moon's bulk composition and thermal history requires answering the questions posed below. Thus, this question will not be answered without extensive lunar exploration.

Was there a magma ocean?

The idea that the Moon was surrounded by a vast layer of magma when it formed, the "magma ocean," has been a tenet of lunar science since it was proposed soon after the return of the first batch of lunar samples, yet this concept is far from proven. The main line of evidence for an ancient magma ocean is the presence of a crust greatly enriched in plagioclase feldspar, hence in aluminum. However, whether the crust truly is enriched in aluminum is not known with certainty because of sparse sampling and incomplete global geochemical coverage (Fig. II-1). We need to determine the amount of aluminum enrichment in the crust by mapping the Moon geochemically and sampling selected areas of the far side.

If there was a magma ocean, what was its nature?

If the nascent Moon was enveloped by an ocean of magma, other planets might have been as well, so it is important to determine what processes operated in it, what products were produced, and how deep it was. The record of magma ocean processes may be preserved in the ancient lunar highlands, possibly in outcrops of rocks called anorthosites, which are rocks composed mostly of plagioclase feldspar. Reading this record will require extensive field work on the Moon.

What is the full range of highland rock types and how are they related to each other?

Besides ancient anorthosites, Apollo samples indicate that the major rock types in the Moon's highland regions are a diverse group called the "Mg-suite". Earth-based remote sensing data for large craters suggest that we have not sampled the full range of lithologies that exist in the lunar highlands. We do not know how these rocks are related to each other or to the anorthosites. Understanding the Mg-suite will shed light on the Moon's magmatic history and further test the magma ocean hypothesis. The answer to this question awaits a global geochemical survey, reconnaissance sampling, and field work.

What is the nature and origin of KREEP?

KREEP is an acronym describing an exceedingly diverse suite of materials characterized by enrichments in potassium (K), rare-earth elements (REE), phosphorus (P) and many other elements. The answer to this question has proven to be one of the most elusive in lunar science; the origin of KREEP seems to have involved the magma ocean and subsequent melting processes inside the Moon. We will know more about it by sampling sites identified from orbit by their enrichments in Th, U, and K.

What is the full range of mare basalt compositions?

Remote sensing suggests that we have sampled less than half of the types of mare basalts that exist on the Moon. Because mare basalts originated by partial melting in the Moon's mantle, this lack of information about basalts hinders our understanding of the lunar mantle. We can inventory the full range of mare compositions by mapping the Moon geochemically from orbit and by sampling unvisited mare flows.

What is the source of volatiles in volcanic glasses?

Although the Moon is depleted in volatile elements, volcanic glass beads, such as the orange glass discovered at the Apollo 17 site, contain deposits of volatile substances (e.g., halides and zinc) on their surfaces. We do not know where in the Moon these volatiles originated. Some source of volatiles must

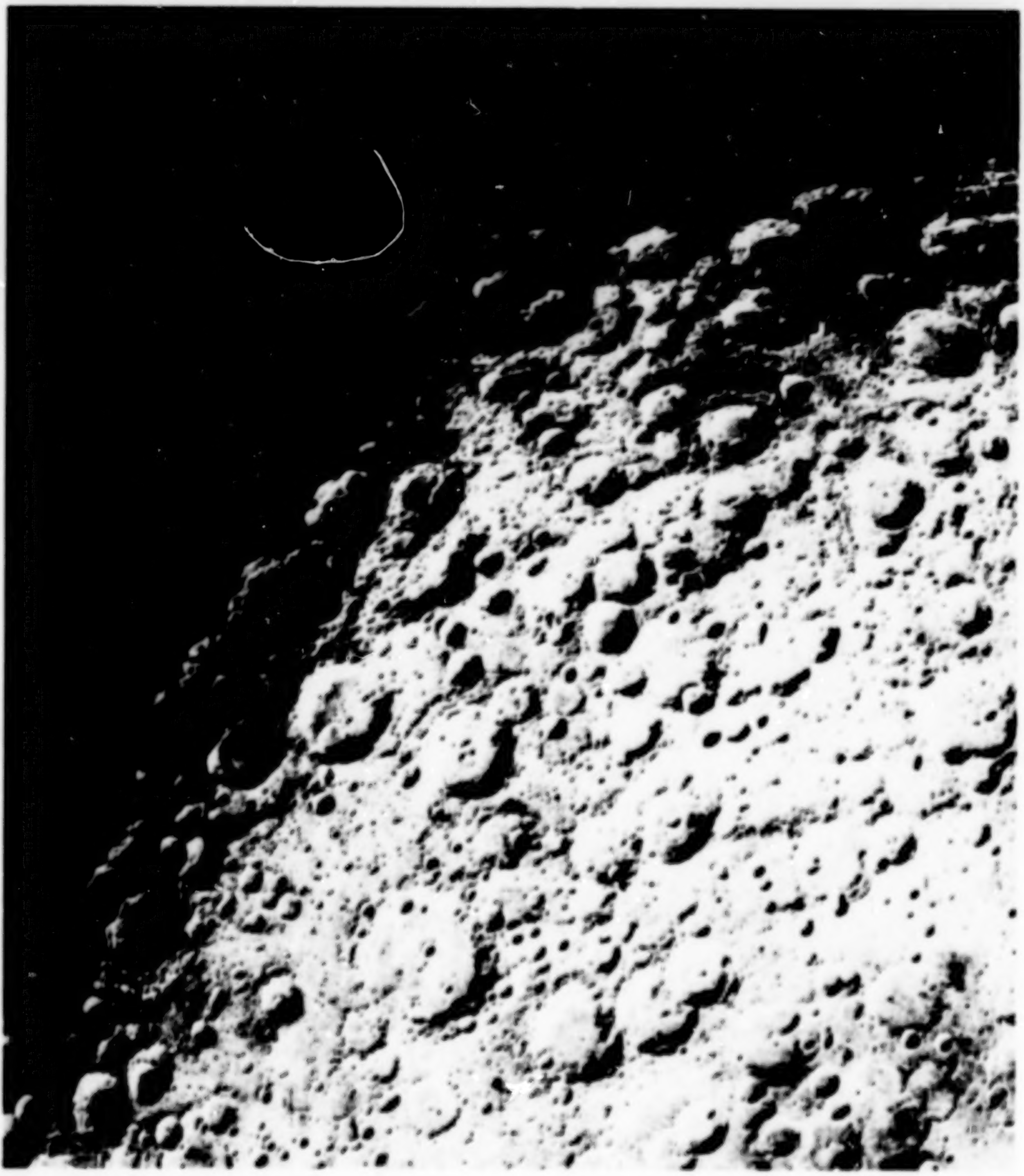


Figure II-1. Ancient cratered highlands on the far side. If the magma ocean hypothesis is correct, such areas uncontaminated with basin ejecta ought to be rich in aluminum. However, only sparse orbital geochemical data and no samples exist for the ancient highlands. Apollo metric photo AS 16-3032.

have been present in the lunar interior and this source could be unmelted, primordial material. If so, answering this question might help us understand how the Moon was assembled. Information about the source of the volatiles may come from an understanding of the total inventory of volatiles present in the gas phase during an eruption. This understanding will require detailed sampling of volcanic glass deposits and field work to search for and study the vents from which they erupted.

How did eruption rates change with time?

An important measure of the thermal history of a planetary body is the rate of lavas eruption and its change with time. Our knowledge of this parameter for the Moon is extremely meager. We know that mare-type basalts began to be erupted about 4.3 billion years ago. Age determinations of samples from the maria indicate that much mare volcanism took place between 3.7 and 3.1 billion years ago, but photogeologic evidence suggests that volcanism may have continued to as recently as 1 billion years ago. Unraveling how eruption rates varied with time will require a combination of reconnaissance sample return missions and detailed field studies in selected areas, especially in the highlands to characterize ancient mare deposits.

What is the nature of the lunar mantle?

Information about a planet's mantle is obtained from seismology and other geophysical measurements, high-pressure experiments and compositional modeling on lavas derived from the mantle, and study of pieces of the mantle (xenoliths) brought up from depth by the lavas. Our knowledge of the lunar mantle is meager, especially for the lower portions. Consequently, the Moon's bulk composition, a key parameter in testing hypotheses of origin, is poorly constrained. No xenoliths of the lunar mantle have been found in Apollo samples; extensive field work will be required to find such occurrences. High-pressure experiments have shed light on portions of the mantle, but many more experiments need to be done on compositions of as yet unsampled basalts. Finally, although the Apollo seismic network operated for eight years, the Moon's low seismicity, the infrequency of large meteorite impacts (which provide seismic signals), and the restrictive distribution of the stations do not allow one to make firm conclusions about the lunar interior. A long-lived global geophysical network is needed to fully understand the mantle of the Moon.

Does the Moon have an iron core?

Available data suggest that the Moon may have a small metallic core, but its size and composition are unknown. Determining its size through seismic studies will help distinguish among models for lunar origin and will allow rigorous interpretation of global geophysical measurements such as moment of inertia. Such studies may also shed light on the origin of lunar paleomagnetism.

What is the origin of lunar paleomagnetism?

Although no magnetic field is being generated inside the Moon at present, measurements from orbit during the Apollo missions and returned samples demonstrate a pervasive magnetization of the crust. It is critically important to our understanding of lunar history and planetary magnetism in general to determine if the magnetization was caused by a core dynamo, as in the Earth, or to local-scale processes, such as impact. This understanding will come only after global magnetic measurements from orbit and from careful collection of oriented samples of mare basalts and impact melt rocks.

How does the crust vary in composition, vertically and horizontally?

Remote sensing and Apollo samples show that the lunar crust is heterogeneous. To decipher lunar igneous history and determine the Moon's bulk composition, we must know the answer to this question. This will require global geochemical mapping from orbit, establishment of a geophysical network, reconnaissance sample-return missions, and detailed field work.

Was there a cataclysmic bombardment 3.9 billion years ago?

A tight clustering in the ages of impact melt rocks in the Apollo collections has led some investigators to propose that the Moon experienced a pronounced increase in cratering rate 3.85 to 4.0 billion years ago. Other scientists argue that the clustering indicates that the Apollo missions sampled only one or two large basins. Resolution of this problem is critically important because a cataclysmic bombardment could have affected the Earth and other planets and their satellites as well. If there was a cataclysm, a mechanism for storing projectiles for 500 to 600 million years must have existed; the existence of such a mechanism has implications for lunar and planetary accretion. To answer this pressing question we must determine the ages of the melt sheets of several lunar basins; hence, we must obtain samples from them.

How did impacts affect the lunar crust?

Impacts have greatly modified the Moon's crust, excavating material from depth and hurling it across the surface. We lack a detailed understanding of the compositional effects of impact. For example, we do not know at any specific site the ratio of primary ejecta from a distant crater or basin to local surface material. Some insight into this process will be gained from orbital studies, but substantial progress requires detailed field study of the deposits associated with large basins.

What is the nature of the lunar atmosphere?

Apollo measurements showed that at night the Moon's atmosphere is extremely tenuous, but data on the density and composition of the daytime atmosphere are scanty because the neutral mass spectrometer left on the surface did not operate during the daytime. The nature of the lunar ionosphere needs to be established more firmly in order to understand the interaction of the solar wind with the Moon, to be sure radio observations in the 1 to 10 MHz range will be possible, and to monitor the evolution of an artificial atmosphere produced by lunar base activities. These measurements can be done by instruments deployed along with geophysical stations.

To answer the questions posed above we need much more information. We need information about the magmatic history of the highlands crust and the characteristics of mare basalts. We need to calibrate lunar stratigraphy quantitatively and determine the nature of the Moon's interior. To accomplish this, we must characterize the geology and petrology of complex sites by doing extensive field work on the Moon.

Although we know quite a bit about our nearest planetary neighbor, many of the details of lunar origin and geologic evolution remain conjectural. The Moon is a small planet of fascinating subtlety and complexity; it is an object shaped by familiar, yet only vaguely understood processes. The Moon is a natural laboratory for the study of planetary geologic processes; this attribute, combined with its accessibility, make the Moon a logical target for human exploration and exploitation.

III. LUNAR RESOURCES

The Moon is the nearest source of extraterrestrial resources that might provide material and fuel for use in space, or, eventually, in support of a lunar colony. The rationale for the use of extraterrestrial materials is economic. It requires more energy to ship materials from a body with a high gravity, such as Earth, than from a body with low gravity, such as the Moon. It may be possible to produce and deliver some extraterrestrial materials to low Earth orbit or to other points in space for a combined cost of production plus transportation that is cheaper than the cost of using material from Earth. Thus, we need to understand what resources the Moon has available. It seems unlikely that in the immediate future there will be any product of extraterrestrial origin that would be less expensive to use on Earth than some native material (although it has been speculated that solar ^{3}He found on lunar dust grains might be a contender as fuel for commercial fusion reactors on Earth.)

What resources does the Moon offer? Our sampling of the Moon is minuscule and we lack global geochemical maps of the lunar surface, so our knowledge is limited. For example, we have not observed concentrations of minor or trace elements in lunar materials comparable to those of terrestrial ores. We are not certain that such concentrations ever existed or, if they did, that they would have survived dispersal during impact cratering events. From our studies of lunar samples, we know what materials are common and that extensive geochemical separations occurred; we have reason to believe that high-grade concentrates of a variety of elements may have been produced. A substantial research effort should be made to improve our knowledge of possible lunar ore-forming mechanisms. This effort should begin with global geochemical remote sensing, followed by more localized studies such as detailed study of materials that can be collected at a lunar base, higher resolution remote sensing, rover-transported geochemical sensing, and sample collection. These studies are part of the basic scientific characterization of the Moon as a planet, as well as a means of finding the Moon's best available resources. From these studies, we can anticipate surprises that will affect both our general understanding of the nature and origin of the Moon and our understanding of its resources.

KNOWN RESOURCES

What do we know so far? From the Apollo and Luna samples, we know that the Moon is basically a very dry, silicate planet. The principal materials on the lunar surface are fine-grained soils. Their major element compositions lie within the range that can be made from mixtures of very calcic feldspar (a calcium-sodium silicate mineral), pyroxene (a magnesium-iron-calcium silicate), olivine (magnesium-iron silicate), and ilmenite (an iron-titanium oxide mineral). Lunar soils are derived from fragments of rocks that consisted mainly of these minerals. Most individual grains of the soils are one of the following materials: lithic fragments of the major rock types (anorthosite, rich in plagioclase feldspar; norite, with roughly equal proportions of plagioclase and Mg-rich pyroxene; troctolite, with varying proportions of plagioclase and olivine; dunite, consisting mainly of olivine; mare basalt, with roughly equal proportions of plagioclase and pyroxene, but sometimes including substantial ilmenite); fragments of individual minerals, where breakup of the parent igneous rock has released them; glassy agglutinates, produced by melting together of soil grains, with lithic and mineral fragments entrapped within the glass; and melt rocks, which are igneous materials produced by impact melting of soils. Soils in mare regions consist mainly of material derived from mare basalt, but because maria are relatively thin, they also contain some highlands material excavated from beneath. Some collected highlands soils are nearly free of mare basalt components.

On the lunar surface, rock is less abundant than soil (Fig. III-1). In the regolith of the maria, chunks of mare basalt are common. In the highlands, nearly all rocks are breccias, i.e., rocks consisting of fragments (clasts) of other rocks held together in a matrix of pulverized and sintered or partly melted rock powder. Some clasts are themselves breccias. Some breccias are composed of a single rock type, but most contain two to several types of lithic clasts. From these breccias, and our knowledge of lunar cratering, we infer that, to a substantial depth, most of the early rock formations of the highlands have been converted to breccia. Lunar mountains presumably consist mainly of breccia while the maria are composed of igneous basalt, which could be seen in layered outcrops at Hadley Rille. Undoubtedly, we can mine breccia and basalt; however, lunar soil is the principal surface material, and at the surface, only chunks of mare basalt and of breccia are readily available.

We have enough information about the Moon from the Apollo and Luna missions to make qualitative generalizations about the physical conditions of the lunar surface. Our quantitative knowledge of the physical nature of the surface is more limited. We

Figure III-1. The regolith is the most accessible resource on the Moon. This photograph shows James Irwin digging a trench at the Apollo 15 landing site.

do not understand the physical properties of the regolith below a depth of about two meters. We know the depth to bedrock only approximately; we are not sure what bedrock means in the sense of being able to support loads. We do not know whether it would be possible to tunnel easily or safely into the lunar surface. We must improve our knowledge of basic geotechnical parameters; in addition to locating lunar materials that we may wish to use, we must design proper equipment for mining and processing them and we must identify early any impediments to accessing them. Lunar igneous rocks have extremely low concentrations of indigenous H N, and C, and we infer that these elements are present in exceedingly low concentrations ($< 1 \mu g/g$) in the lunar interior. Most of the Moon's budget of H, C, N, and noble gases is found within the outer fraction of a micron of soil grains, where it has been implanted as ions from the solar wind. These elements are thus dispersed (C, H, and N $\sim$ 50-100$\mu g/g$ in most soils) but their overall abundances are substantial. There is a possibility that higher grade deposits of volatiles exist in permanently shadowed areas at the lunar poles, where water and carbonaceous material might have been cold-trapped from a temporary atmosphere produced by the impacts of comets. From the lack of H and C in the interior of the Moon, we infer that the range and types of ores that we find on Earth are absent on the Moon, because nearly all terrestrial ore-forming processes involve water and other relatively volatile materials.

The concentration of incompatible trace elements (examples include the alkalis other than Na, rare earths, Zr, Th, and U) varies by factors of several thousand. The observation of a wide range in concentration is important because it indicates that substantial geochemical separation has occurred despite the absence of water and other volatile substances. Incompatible elements are found in very low concentrations in the minerals olivine, pyroxene, and feldspar, and in the rocks that consist of those minerals, except when significant proportions of accessory minerals are also present. Phosphate minerals and zircon are the most common accessory minerals rich in incompatible trace elements, sometimes reaching proportions of several percent. The materials richest in these elements were collected from the Fra Mauro region (Apollo 14).

Volatile elements (Zn, Se, Ag, Cd, Pd, halogens, and alkalis) are relatively depleted on the Moon's surface as compared with the Earth's surface. Some of them also are transported in the vapor phase when sufficient heating from meteoroid impact occurs. Their concentrations in soils are substantially enriched over their concentrations in igneous rocks because of contributions of meteorites to the lunar soils. Infalling meteoritic matter makes up some 1-3% of a typical soil; like the indigenous lunar matter in the soils, these meteoritic components have been pulverized.

Lunar igneous rocks are very deficient in siderophile elements (e.g., Ni, W, Pt, and Au) even relative to terrestrial igneous rocks. Like the vapor-mobilized elements, siderophiles are enriched in the soil by meteoritic addition. However, they tend to be found in the metallic phases of meteorites, mainly Fe-Ni alloys, which can be concentrated by simple magnetic separation. This process yields a metal-rich material, but not pure metal (many of the metallic fragments are entrapped in agglutinates and melt rocks.)

REMOTE SENSING AS A PROSPECTING TOOL

Remote sensing from orbit, such as that proposed for the Lunar Observer mission, is a vital first step toward our understanding of the regional distribution of different materials at the lunar surface. Because most material at the surface comes from directly beneath it (despite some lateral movement of material during impact cratering), it is believed to reflect the nature of the underlying material to depths of kilometers. The extent of compositional variation we find will enable us to determine the Moon's crustal differentiation and geochemical structure; these are important parameters for theoretical considerations of lunar ore-forming processes. Global remote sensing will enable us to determine directly the concentrations of several major elements, and from that, infer what rock types may be present. It will also enable us to observe directly where the highest concentrations of major and minor elements are found, regions that someday we may regard as high-grade ores.

The incompatible trace element thorium is radioactive and its surface concentrations can be determined precisely by gamma-ray remote sensing from orbit. Because the incompatible trace elements behave as a coherent group during most geochemical separation, high Th concentrations can be used to infer the locations of relatively high concentrations of other trace elements. Based on the Th mapping of the equatorial band overflown by the Apollo 15 and 16 gamma-ray experiment, we know that the Imbrium-Procellarum region contains sizable areas of high thorium concentration. Several small regions of high concentration were noted elsewhere. However, this gamma-ray experiment observed only about one-fifth of the Moon's surface. A properly equipped polar orbiting spacecraft could refine and extend globally our knowledge of surface concentrations of major and trace elements. We will probably find unexpected materials as our knowledge of the lunar surface increases. Even if we did not, we would find the highest grades of the types of materials we already know are present, for example, the soils with the highest Ti concentrations, or those expected to contain the highest concentrations of C, H, and N. We cannot determine everything we need to know about resources from orbit. Ground observation and sampling will also be required.

POSSIBLE PRODUCTS

The only materials we can rely on now as resources are those that we know to be abundant and common on the lunar surface. Even if the Moon has no better "ores" than its most common materials, much can be done with lunar soil. Without processing, the soil can be used for radiation shielding. Melted, it can be cast into plates, beams, and pipes for construction, or spun into fibers. Subjected to more complex processing, it can yield oxygen (the most abundant element on the Moon) for life support and for fuel oxidizer, an anticipated near-term need. Magnetically concentrated, it can yield meteoritic metal that can provide iron (which can also be a byproduct of oxygen extraction) for construction and electrical conduction, a resource that will be needed later in the evolution of a lunar base. Under severe chemical processing, it can yield aluminum. Heated, it can evolve H (and thus provide water), C, N, and noble gases for both life support and fuel production. Quantities of all these materials are large; we know we can count on the lunar soil! We might not at first recognize common lunar materials as desirable resources, because they are so different from the corresponding sources of the same material we would use on Earth. We do not, for example, obtain our oxygen from decomposition of silicate rock (other organisms do that for us). Nor do we obtain our water by extracting hydrogen from soil and reacting it with oxygen. Nor might we give thought to very simple materials whose presence we might assume if we depend too much on analogy with Earth. An example is gravel, which we might need for applications such as improving the bearing strength of lunar roads. The areas of the lunar surface we have visited consist of very fine dust with relatively sparse particles as large as a centimeter in diameter; gravel would be a scarce quantity, probably too expensive to collect as a primary product. It could be an important byproduct of hydrogen production from large volumes of soil.

For construction in space, we need to determine what materials are cheapest and easiest to obtain, as opposed to what materials might be the most desirable if we were obtaining them from Earth, or what materials we traditionally have used for a given purpose. For example, concrete, steel, and aluminum are commonly used in construction on Earth. Most engineers contemplating large structures in space propose to make them from aluminum. These structures might be cheaper if glass replaced metal as a major component. On Earth, we use copper for electrical conductors; on the Moon, copper is not abundant, and copper ores are unknown. Aluminum is a good conductor, and in space would not oxidize causing the problem of poor connection when used on Earth. However, it appears to be easier to wrest iron than aluminum from lunar material, and iron can readily conduct electricity if we use wires of somewhat larger diameter than we are accustomed to. These examples are given to illustrate how we must revise our thinking in order to make optimum use of lunar material and to recognize what materials are actually resources.

Resource surveys can improve our ability to select a site for the first lunar base. They are also an investment in the future, when there may be a lunar settlement of substantial size. What we propose is prospecting in a sense, but initial surveys will stem from those experiments intended to enhance our general knowledge of the Moon as a keystone example of a small planet and a recorder of the early history of the Earth and the Solar System. Only later would missions be sent to selected sites to test the promise of local resources.

IV. GLOBAL SURVEYS

Both orbital and surface measurements on a global scale are needed to resolve many basic issues in lunar science and to assess resources for future utilization. Currently, these measurements are woefully incomplete in spite of the important accomplishments made during previous exploration of the Moon. Orbital data will receive a major augmentation from the U.S. Lunar Observer mission planned for the 1990's. New surface measurements may occur via a network of automated geophysical stations prior to or after establishment of a permanently-staffed lunar base. In this chapter, we discuss the general nature of these essential measurements and their relevance to geoscience and resource utilization.

THE LUNAR OBSERVER MISSION

The Lunar Observer (LO) is slated to follow Mars Observer as the next mission in NASA's Observer series although it has not yet been approved for funding. Currently, it is planned that the mission will use the same type of spacecraft (Fig. IV-1) as the Mars Observer although significant revisions of the instrument payload will be necessary. LO will study the Moon for at least a year in its near-polar orbit. This much time is essential to map quantitatively the Moon's geochemical, mineralogical, and geophysical properties on a global scale. Because of the current lack of global coverage (Figure IV-2) and the need for such coverage in preparation for future manned or unmanned surface missions, LO is the next logical step in lunar exploration. This section summarizes planned LO measurements and the ways in which the data will address the science questions raised in Chapter II. For a more detailed discussion, see Lunar Geoscience Observer Working Group Members (1986).

The Lunar Observer Instruments and How They Will Address Unsolved Problems

The Solar System Exploration Committee has recommended to NASA that LO carry the following devices, with the first three instruments (and radio subsystem) making up the minimum suggested payload:

X-ray and gamma-ray spectrometers

The X-ray and gamma-ray spectrometers (XGRS) will produce global maps of elemental abundances of the lunar surface. The bulk composition of the Moon is an important constraint on hypotheses of lunar origin. In determining how closely the Moon and Earth are related, two of the most useful parameters are the abundances of uranium and thorium and the ratio of magnesium to iron. LO will produce an accurate map of the surface distribution of uranium and thorium, which can be used to estimate the global abundances of other elements of similar geochemical behavior. LO will also determine the ratio of magnesium to iron over broad areas of the surface to within 3 %. When this information is combined with the higher spatial resolution data on crustal heterogeneity from the visual and infrared spectrometer (see below), the bulk properties of the lunar crust can be estimated to compare with aspects of Earth's composition.

Maps of elemental abundances can be used to constrain the distribution of rock types and to identify new ones. The limitations on how well this can be done will not be set by limitations of the instruments carried by LO, but by the jumbled nature of the crust, the areal extent of outcrops, and the distinguishing characteristics of unknown rock types. These maps can also be used to determine the abundance and distribution of plagioclase, knowledge that is crucial for assessing models of the magma ocean.

Measurements of the composition of crater and basin floor deposits can address the problem of whether impact melts are homogenized by looking for compositional variations within the melt sheet resting on crater floors. If ejected melt deposits are found around craters and basins, it is important to establish their compositional affinities to the main melt sheet inside the structures. In general, XGRS and VIMS (see below) will provide direct information about impact and its effects on not only the Moon, but on other planetary surfaces as well.

The composition and extent of unusual deposits or potential resources can also be studied with the X-ray and gamma-ray spectrometers. For example, the gamma-ray spectrometer could determine if ice is trapped in permanently shadowed areas near the lunar poles. Also, determinations of elemental abundances in glassy deposits can be used to constrain the history of these materials.

Visual-infrared mapping spectrometer

The visual-infrared mapping spectrometer (VIMS) will provide a global assessment of surface mineralogy at high spatial resolution (1/2 km). VIMS can be used to determine the distribution of

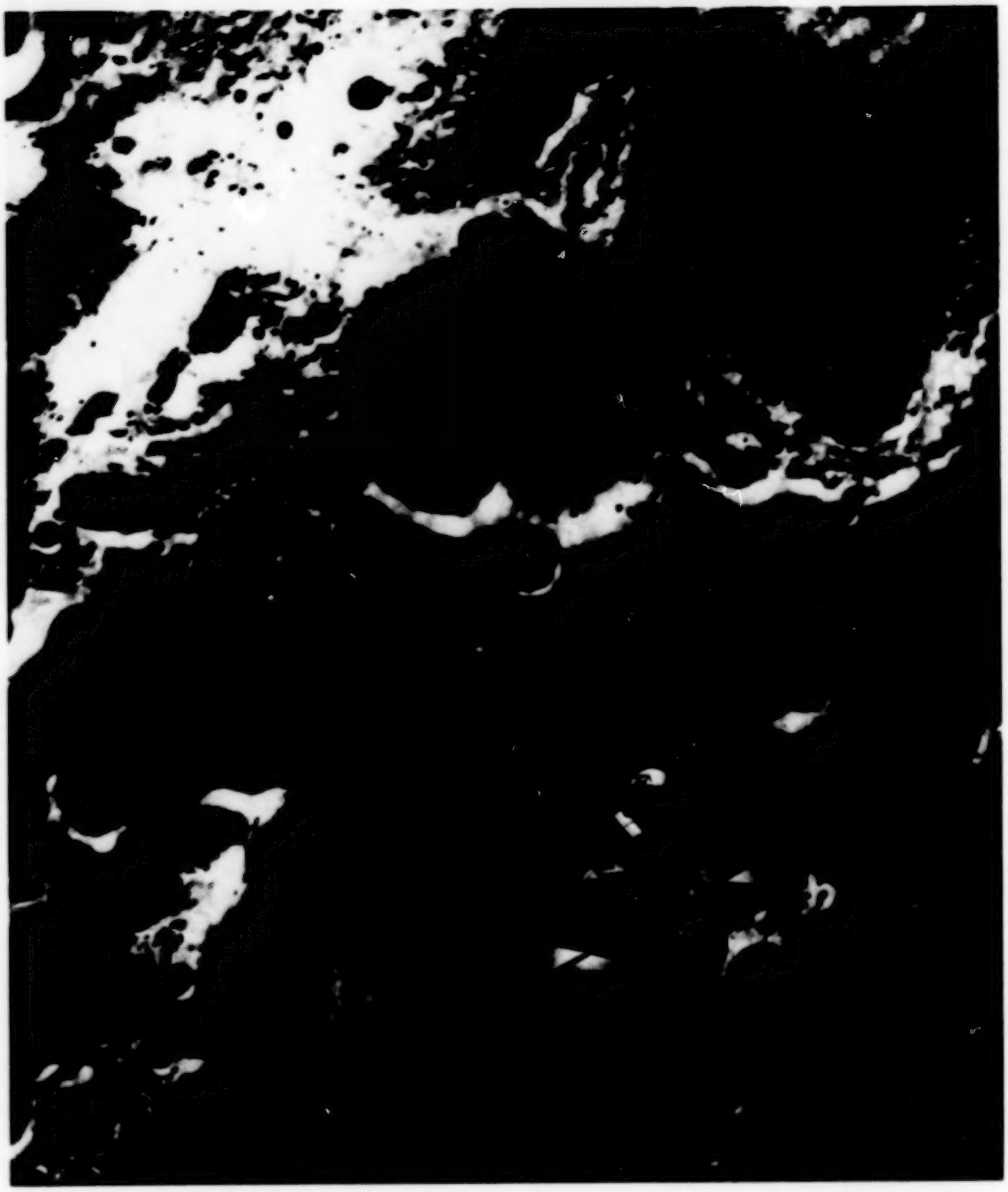


Figure IV-1. Artist's conception of the Lunar Observer spacecraft, which will provide global geochemical, mineralogical, and geophysical data about the Moon.

highland and mare rock types and to identify those that are presently unknown. It can also be used to map the distribution of glassy deposits. VIMS tells what minerals elements are located in and is particularly useful in combination with the X-ray and gamma-ray spectrometers, which tell what elements are present.

VIMS data can be used to address important science questions regarding lunar crustal heterogeneity and structure. For example, the idea of a magma ocean depends on the notion of a plagioclase-rich crust. Although available data from rock analyses and remote sensing support this idea, we do not know the average plagioclase abundance or the depth of the plagioclase-rich region. One of the 'most important questions the VIMS can address in consort with the XGRS is the abundance and variation with depth (as revealed by large craters) of plagioclase in the highlands crust.

Altimeter

An altimeter will yield topographic data for geophysical studies and cartography for selected areas. Topographic information can be used to study the thermal history of the Moon because heating and cooling lead to changes in density; these density changes produce stresses that are expressed topographically. Topographic information can also be used in conjunction with gravity measurements to study the lateral and vertical structure of the crust and to refine earlier measurements of the center-of-figure to center-of-mass offset.

Radio science

The radio science experiment will map the gravity field of the lunar near side by measuring the Doppler shift as the spacecraft changes velocity in response to changing gravitational forces along its ground track. These changes typically will be caused by variations in crustal thickness and density, which are crucial parameters in modeling the structure, and hence, the origin and history of the Moon. For example, the gravity measurements can be combined with topographic, chemical, and mineralogical measurements to constrain the amount of plagioclase in the highlands crust.

Magnetometer/electron reflectometer

The magnetometer/electron reflectometer carried aboard LO will produce the first global map of crustal magnetic fields and will measure global-scale induced fields to constrain the size of a metallic core. Detailed investigations of the directional properties of the magnetization of the lunar crust and correlations with surface geology will help to establish whether magnetizing fields were produced by a former core dynamo or by localized impact processes. The results will have implications for the interpretation of paleomagnetism on all other airless silicate bodies in the Solar System. Measurements of the induced magnetic dipole moment during intervals when the Moon is in the geomagnetic tail will allow estimates for the maximum radius of a metallic core. This quantity in turn limits the core mass, a basic constraint on models of lunar origin.

Imaging system

A high-resolution digital imaging system would provide improved global cartographic control, support studies of composition using geochemical data, and allow new studies of specific surface features for which current photography is inadequate. With the exception of Earth-based telescopic images, none of the existing lunar imagery is in digital form and the quality and coverage of these collections is not uniform. Imaging can be targeted to specific areas of interest where current coverage is poor, such as the poles and the Orientale basin, and this instrument will create a global grid for improved geodetic control. Imaging may also be used to help in the selection of sites for outposts and permanent bases.

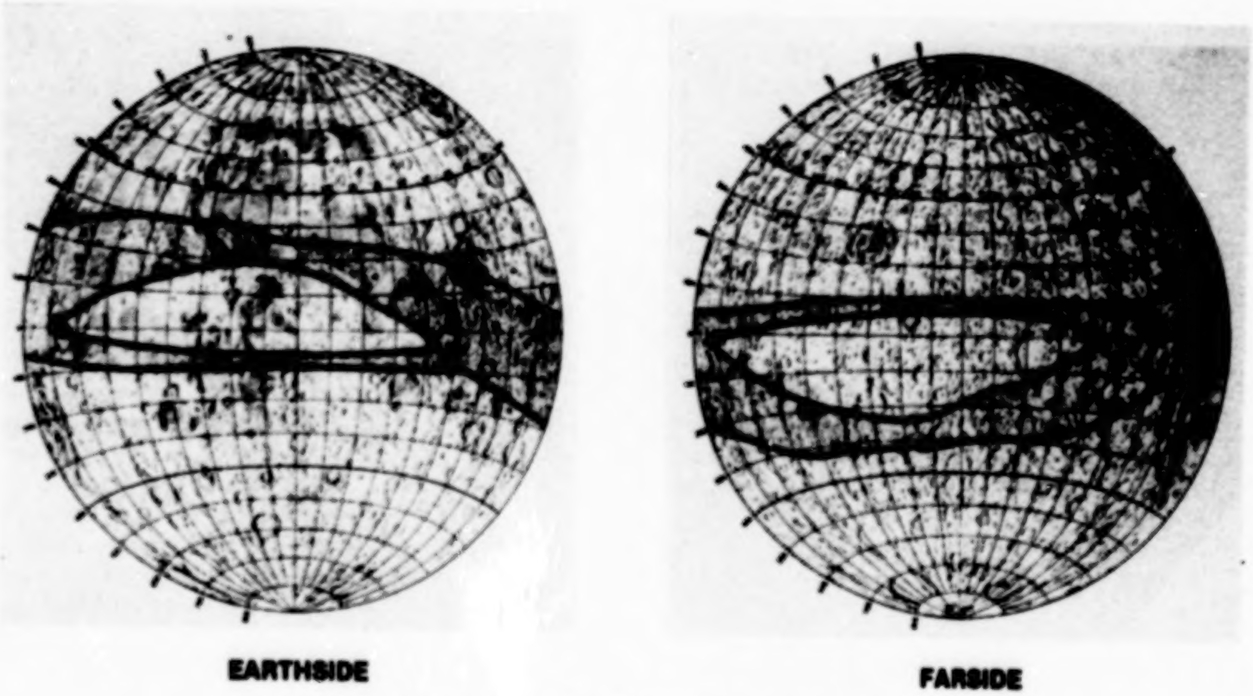
In addition to the experiments recommended by the Solar System Exploration Committee, the following instruments were considered by the Lunar Observer Workshop as candidates for the LO payload:

Microwave radiometer

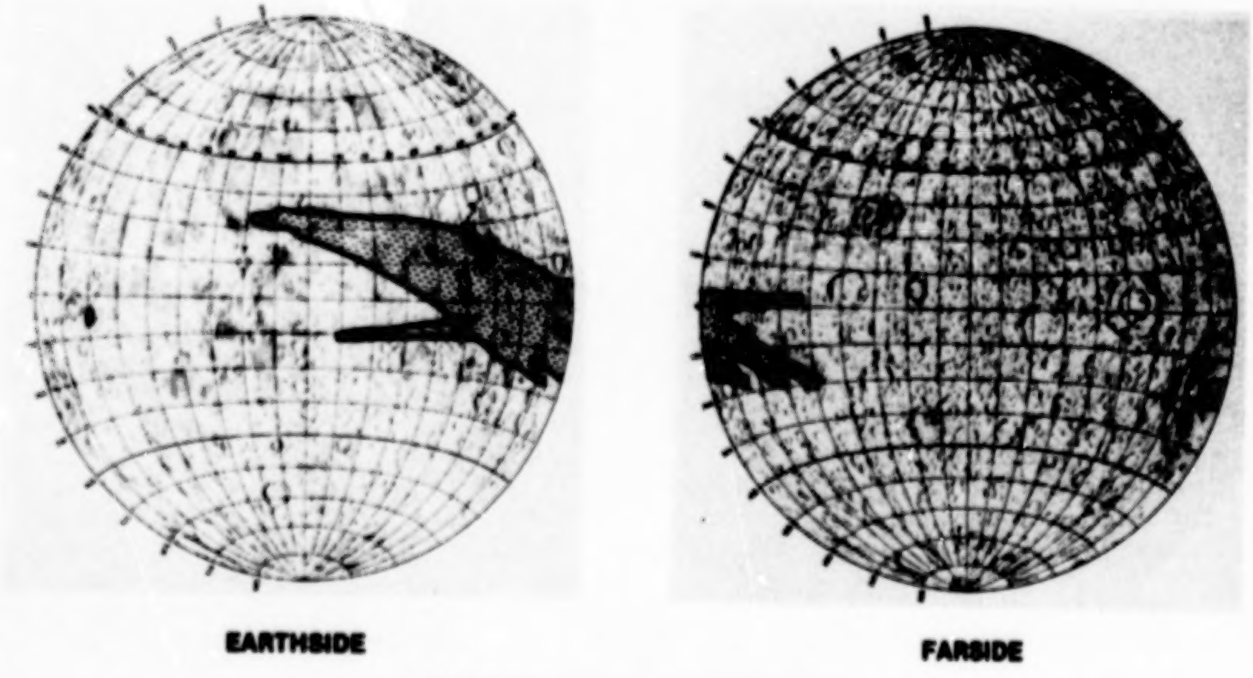
The microwave radiometer would provide a map of lateral variations in heat flow. Such a map, combined with the absolute measurements at the Apollo 15 and 17 landing sites, would more accurately constrain the mean global heat flow which is essential for understanding the thermal history of the Moon. The total heat flow would also constrain the abundance of radioactive elements (U, Th, K) and hence, constrain our estimate of the bulk composition of the Moon. The heat flow at individual sites will depend on both the local abundance of radioactive elements (which will also be constrained by the compositional information) and the local structure of the crust and megaregolith.

Spacecraft gravity system

This experiment would provide essentially the same information as the radio science experiment but would use a small subsatellite to map the gravity field of the lunar far side. The most recent designs


EARTHSIDE
FARSIDE

CURRENT GAMMA-RAY COVERAGE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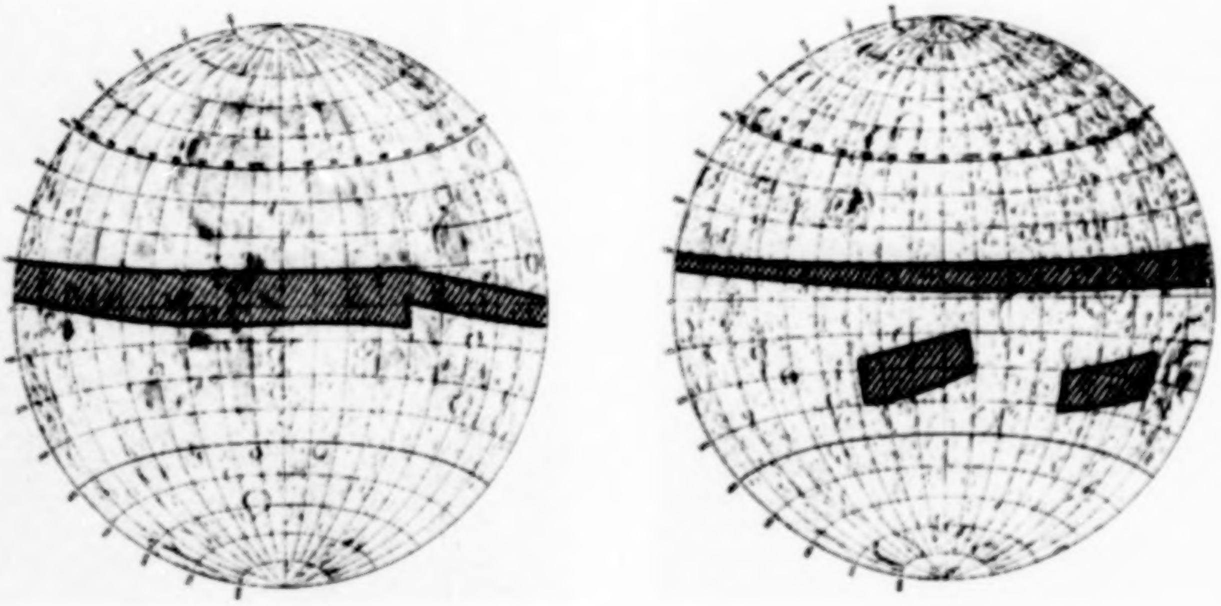
CURRENT X-RAY COVERAGE

Figure IV-2a. Apollo gamma-ray and X-ray coverage of the Moon.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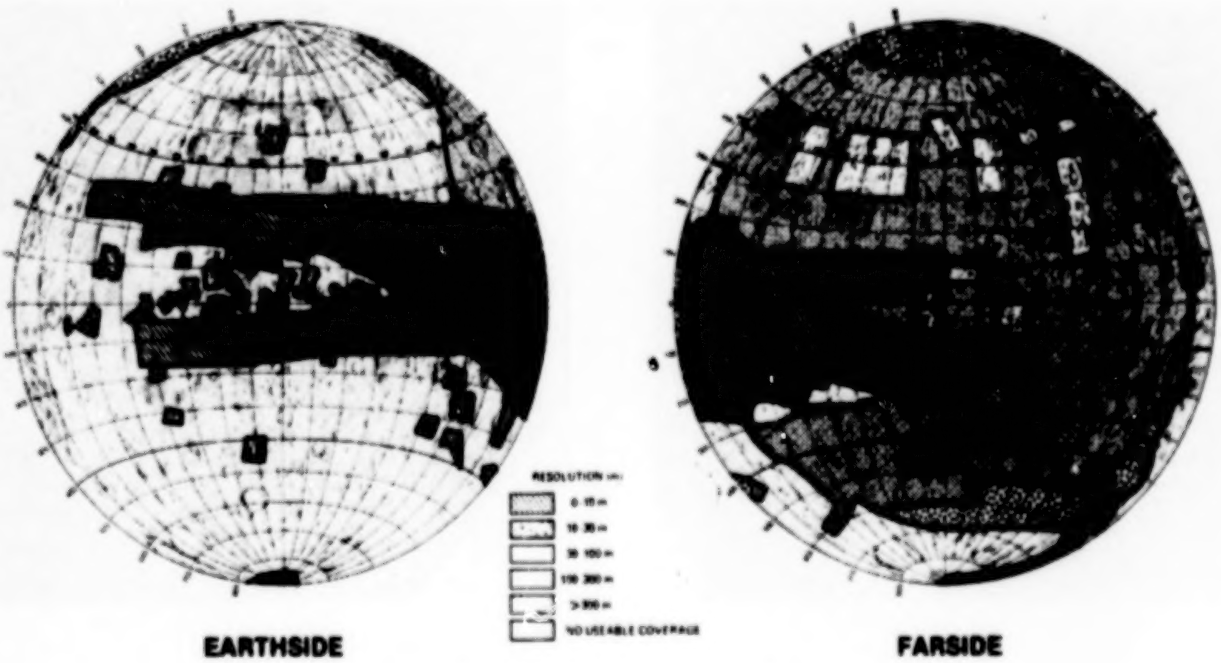
CURRENT USEFUL MAGNETOMETER COVERAGE


RESOLUTION (m)
0-10 m
10-30 m
30-100 m
100-300 m
>300 m
NO USEABLE COVERAGE
EARTHSIDE
FARSIDE

CURRENT IMAGING COVERAGE

Figure IV-2b. Current magnetometer and imaging coverage of the Moon.

for LO include this device in the spacecraft's engineering system, since knowledge of the far side gravity field is essential to maintain a 100-km, circular orbit.

Thermal emission spectrometer

The Thermal Emission Spectrometer would provide additional mineralogical information about surface material that is complementary to that obtained from the Visual Infrared Spectrometer. It may also provide information about the physical properties of the surface.

The Moon is our most accessible natural planetary science laboratory. In addition, many fundamental science issues remain unresolved in spite of intensive study during the Apollo program. LO will make numerous contributions to both lunar and planetary science by obtaining a global data base of geochemical, geological, and geophysical measurements.

Lunar Observer and Future Lunar Exploration

Besides addressing fundamental questions in lunar and planetary science, LO will lay the groundwork for the future exploration of the Moon. The global database this mission produces will allow intelligent selection of landing sites for manned or unmanned sample return missions. It will also allow us to explore for useful materials that are easily accessible from the surface. For example, deposits containing water ice may be trapped in permanently shadowed areas near the poles; if such deposits exist, they would be detectable by the gamma-ray spectrometer. Even small amounts of valuable hydrated materials (resulting from comet impacts) might be readily detected by the high-resolution visible and near infrared spectrometer. In addition, the basic science results concerning the structure and composition of the crust and the processes that shaped it will lead to models of ore genesis on the Moon, which should greatly aid in the search for new mineral deposits. Finally, the information obtained from the LO mission will help in the selection of the site of a permanently staffed lunar base by mapping site geology, topography, resources, and potential safety hazards.

SURFACE GEOPHYSICAL STATIONS

Geophysical measurements such as seismicity, gravity, heat flow, paleomagnetism, and electromagnetic sounding are best determined from the surface and can be used to address a series of global and regional science questions. Global problems include the existence and mass of a metallic core, the compositional structure and thermal state of the mantle, the mean global heat flow, and the origin(s) of paleomagnetism. Examples of regional issues are the compositional structure and lateral variation in thickness of the crust, lateral variations in surface heat flow and subsurface temperature, basin structure and stratigraphy, origin of the mascons, and origin of strong crustal magnetic anomalies. In this section, we concentrate on the application of surface geophysical measurements to solve global and regional problems. As a basis for the design of these measurements, we first briefly summarize major results and problems encountered in the acquisition and analysis of Apollo surface geophysical data.

Apollo Surface Geophysical Measurements

Apollo Seismic Investigations

Although the 4-station Apollo seismic network provided the first useful seismic investigation of an extraterrestrial body, more definitive measurements are needed to determine the nature of the lunar interior. Sources of seismic signals included artificial and natural impacts, weak repetitive deep-focus moonquakes triggered by tidal stresses, and more energetic but rare shallow moonquakes that are most probably of tectonic origin. The total seismic energy release of the Moon was found to be small (less than 10^{11} Joules annually compared to the terrestrial output of about 10^{18} Joules); moonquake magnitudes are as large as 5 on the Richter scale for shallow events and 1.6 for deep moonquakes. Lunar seismograms are more complicated than are their terrestrial counterparts: In addition to the relatively weak source-signal amplitudes, intense scattering occurs in the near-surface brecciated zone, reducing the signal-to-noise ratio and greatly complicating the interpretation of lunar seismograms.

A major objective of Apollo seismic investigations was to determine the P- and S-wave velocity structure of the lunar interior from the measured times of arrival of these waves at stations in the Apollo network. In the case [illegible] near-surface and crustal seismic-velocity models, the inversion problem was simplified through the use of astronaut-activated seismic energy sources and the planned impacts of the Lunar Module ascent stages and upper stages of the Saturn rocket. The known event times, energies, and source locations allowed a relatively accurate model of crustal P-wave velocities to be constructed for the Mare Cognitum region near the Apollo 12 and 14 landing sites.

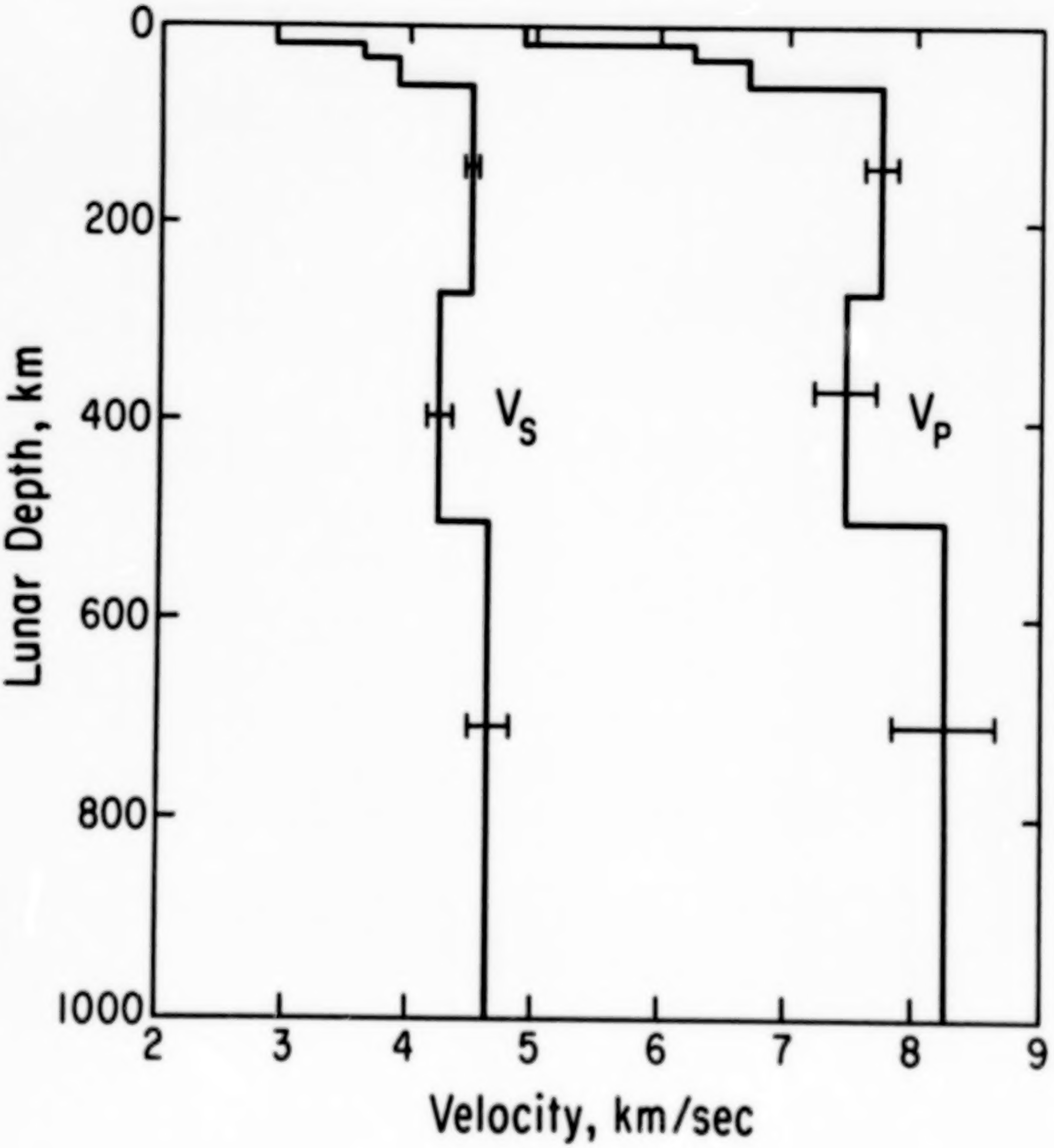


Figure IV-3. Seismic velocity variations with depth, based on work of Y. Nakamura. V_s and V_p refer to seismic shear wave and compressional wave velocities, respectively. Uncertainties in the data upon which these profiles are based do not allow for definitive conclusions about the composition of the mantle.

A continuous increase in compressional velocity between 1.4 and 20 km was inferred and is believed to be due primarily to the effect of crack closure with increasing pressure. A discontinuous P-wave velocity increase near 20 km depth may be indicative of a composition change (e.g., to greater percentages of mafic silicates in addition to the dominant aluminoas anorthosites). Between 20 and 55 km, the velocity was inferred to remain approximately constant before increasing to a distinctly higher value at depths of 60 km. The velocity transition between 50 and 60 km depth is to those characteristic of mantle pyroxenes and olivine and therefore, marks the approximate base of the crust.

The most recent model of mantle seismic velocities (developed by Y. Nakamura) is based on the complete five-year data set acquired when the four Apollo seismometers were simultaneously operative. As shown in Figure IV-3, this model is characterized by a gradual velocity decrease with increasing depth in the upper mantle which is ascribable primarily to increasing temperature in the interior of the Moon. At approximately 500 km depth, however, the velocity profile increases to a substantially larger value than earlier models. Theoretical investigations of the Nakamura model have concluded that the increased velocities in the middle mantle are consistent with the appearance of garnet-bearing assemblages, particularly if the Moon differentiated to about this 500 km depth. However, the systematic and statistical uncertainties associated with the Nakamura model are large, so no absolute conclusions about bulk composition and depth of differentiation of the Moon can be drawn. Similarly, seismic evidence for the existence of a lunar core is not definitive.

Apollo Heat Flow Measurements

Heat flow determinations are needed as a basic boundary condition on the present-day temperature structure of the lunar interior. In addition, they constrain the abundance of radioactive isotopes responsible for heat generation in the Moon. In particular, the global abundance of uranium and thorium may be inferred, providing an independent evaluation of the extent to which the bulk Moon is or is not enriched in refractory elements compared to the Earth and chondritic meteorites.

Heat flow probe measurements were successfully obtained at the Apollo 15 and 17 landing sites, yielding final estimates of 21 and 16 mW/m^2 respectively. These measurements were obtained using temperature sensors emplaced several meters beneath the surface to measure both the vertical temperature gradient and the thermal conductivity of the surrounding regolith. The latter task proved to be the more difficult than anticipated and required analysis of long-term periodic subsurface temperature histories at each site over a period of years. Derivation of globally representative averages from these isolated measurements is model dependent. Both the Apollo 15 and 17 sites are near the edges of maria where megaregolith thickness may be smaller than for the highlands, possibly leading to anomalously high heat flow values. This is further complicated by local enrichments (at least in the near-surface regolith) in the heat-producing elements Th and U, particularly around the Apollo 15 site.

Apollo Surface Magnetometer and Plasma Measurements

As the Moon has no global magnetic field and no ionosphere, it directly experiences changes in the external magnetospheric or solar wind magnetic field. In addition, during most of the month, the solar wind directly impinges on the sunlit surface except for local areas protected by strong crustal magnetic fields.

The primary method for electromagnetic sounding employed during the Apollo program required orbital magnetometer measurements to define the external (forcing) field and simultaneous surface magnetometer measurements to determine the induced magnetic field produced by induction currents in the interior. Inversion of the measurements via a suitable theoretical model then yielded limits on the electrical conductivity of the interior with depth. Conductivity profile bounds were independently obtained from both geomagnetic tail transient data and from solar wind/magnetosheath data and these measurements were in agreement within approximately one order of magnitude at all depths. No definitive evidence for (or against) a highly electrically conducting core (conductivity > 10 $S\ m^{-1}$) was obtained in any of these studies although a probable upper limit of 400-500 km on the radius of such a core was derived. In addition to global-scale sounding of electrical conductivity, evidence for regional electrical conductivity anomalies associated with circular maria on the near side was obtained from analyses of Apollo and Soviet surface magnetometer data.

Several properties of the regolith, including albedo, correlate with the degree of solar wind ion implantation. A complete understanding of these properties requires study of the solar wind interaction with the Moon as a whole and with local crustal magnetic anomalies. Solar wind spectrometer measurements were limited to the Apollo 12 and 15 landing sites where surface magnetic fields were relatively small. At the Apollo 12 site, the surface field was large enough (38 nT) to produce small but measurable perturbations in the parameters of the incident plasma. In particular, solar wind protons were observed to be decelerated by as much as 70 km/s and to be deflected in direction by as much as 10 degrees. Unfortunately, no data were obtained at other sites such as the Apollo 16 site, where surface fields as large as 327 nT were measured. Surface fields at sites of the strongest anomalies observed from orbit probably exceed 1000 nT and will interact strongly with the incident solar wind.

Apollo Atmospheric Measurements

In spite of Apollo measurements, the tenuous lunar atmosphere and processes operating within it have not been studied adequately. Such studies yield interesting information about planetary outgassing and the interaction of the solar wind plasma with a tenuous atmosphere. Several atmospheric and ionospheric monitors were used during the Apollo missions. The Cold Cathode Gauge Experiment (CCGE) measured total atmospheric pressure and found a total nighttime concentration of 2×10^5 molecules/cm^3. The Lunar Atmosphere Composition Experiment (LACE) was a neutral gas mass spectrometer, designed to measure the abundances of gaseous species in the atmosphere. Unfortunately, it acquired useful data only at night. Daytime concentrations were not determined directly, although modeling of atmospheric dynamics and predawn increases in CO_2 and other carbon-bearing molecules suggest that such species dominate the daytime atmosphere. The third Apollo instrument was the Suprathermal Ion Detector Experiment (SIDE), which detected ions present in the atmosphere, thereby monitoring an important loss mechanism. Finally, the lunar plasma environment and surface photoelectron density were measured by the Charged Particle Lunar Environment Experiment (CPLEE) and the Solar Wind Spectrometer (SWS).

Future Measurement Requirements

Distribution and length of operation of stations

The single most important deficiency of the Apollo geophysical network was the small number and poor areal distribution of stations. Future seismic, heat flow, and electromagnetic sounding measurements obtained over a sufficiently long time (decades) at widely separated stations around the Moon will result in much better constraints on the density variation, bulk composition, and thermal structure of the interior. Atmospheric monitors with a similar wide distribution will determine atmospheric dynamics and composition, provided that the measurements are obtained prior to strong contamination of the lunar environment by manned activities. External plasma monitors will help determine those properties of the surface and regolith that are dependent on the solar wind ion bombardment.

In principle, detection of a metallic core can be achieved with as few as four seismic stations, two located on opposite sides of the Moon and the others located at intermediate angular distances. Occurrence of a number of large meteoroid impacts or shallow moonquakes near the two antipodal stations would provide the needed seismic energy sources. However, a network of eight stations would improve the quality of the data substantially. Consistent detection of substantial P-wave arrival delays at the opposite station as checked by arrivals at the intermediate stations would prove the existence of a low-velocity core (expected for a core with a dominantly iron composition). Japanese scientists are currently planning such a core detection experiment using seismometers to be deployed by penetrators in the late 1990's.

In order to establish with greater precision the seismic velocity structure of the crust and mantle, as needed to constrain the bulk composition, the depth of initial melting, and crustal composition and thickness, a series of regional passive seismic networks are needed. Detailed near-surface crustal structure could be investigated using Apollo-type active seismic sources near single stations. A series of regional networks ultimately would establish the seismic velocity structure of the mantle. These networks would simultaneously establish the nature of lateral variations in crustal thickness and upper mantle velocity structure, as well as provide an alternate determination of the existence, size, and probable mass of the core.

The requirements of wide distribution and long operating periods for seismometers are shared by other geophysical instruments including heat flow probes, magnetometers, atmospheric and plasma monitors. Co-location of these instruments in geophysical stations analogous to the Apollo lunar surface experiments package (ALSEP) therefore is preferred. Specific recommendations for individual instruments are given below.

Seismometry

We recommend that three-component seismometers with a better sensitivity than that of Apollo seismometers be deployed in a series of regional networks. Specifically, ground motion sensitivity should be less than 0.3 nm (preferably, 0.03 nm) and the frequency bandwidth should extend at least between about 30 Hz and 0.03 Hz. In order to minimize thermal effects, it is desirable that the instruments be emplaced at least 1 meter beneath the surface. Emplacement in deeper bore holes could also reduce the near-surface scattering of seismic waves that was an impediment to the interpretation of Apollo seismograms. The capability to measure long-period free oscillations of the Moon is a desirable attribute of future lunar seismic instruments. The functioning operating period of a global seismic network should be at least ten years.

Each regional seismic array must consist of at least four seismometers in order to determine the four unknown variables of a typical event, i.e., epicenter and focus locations, intensity, and time. Because deep moonquakes originate at depths as large as 1000 km, the surface separation of stations in the regional array should be comparable in length. For example, three stations could be located at the corners of an equilateral triangle with 1000 km sides and the fourth could be located at the center of the triangle. Of course, the addition of stations to the array would provide redundancy in case of hardware failures and would increase the accuracy of inversions. To obtain an adequate global data set, a minimum of four regional arrays whose centers are located equidistant from one another is suggested. Such a configuration would allow S-waves from any one deep moonquake source to be detected by at least two arrays. A lesser number of arrays would result in S-waves being absorbed by the zone of low seismic Q-values (high attenuation) deep in the lunar interior before reaching all but one of the regional arrays.

In addition to regional arrays, local arrays with smaller separation distances should be established to study shallower structure including variations in crustal thickness and the subsurface structure of basins. Active seismic sources (such as impacts of expended rocket boosters and explosive charges used during the Apollo missions) may provide the most efficient means of determining near-surface crustal structure near single stations.

Heat flow

As indicated previously, heat flow measurements at the Apollo 15 and 17 mare sites may not be representative of the Moon as a whole. Consequently, future measurements must be obtained from sites with a greater variety of geologic settings. In particular, measurements at highland sites on both the near and far sides and at sites near the centers of circular maria would be most useful in establishing the true global average heat flow. To obtain an accuracy comparable to Apollo measurements, detailed analysis over a period of years of subsurface temperature measurements at each heat flow measurement site is required. Ground truth heat flow values at the selected sites would complement orbital measurements of lateral heat flow variations by microwave radiometry that might be acquired on the Lunar Observer mission.

From Apollo experience, it is known that a successful lunar heat flow probe must measure the ambient regolith temperature at depths between approximately 0.5 and 1.5 m to an accuracy of about 0.05° K in a temperature range between 200° and 270° K. The thermal diffusivity of the regolith can be determined from long-term measurements of the daily and yearly variations in temperature at these depths. This quantity together with the measured overall gradient (and the specific heat of the soil already derived from Apollo laboratory measurements) determines the heat flow. As discussed earlier in this chapter, orbital measurements of microwave radiance may provide a means of determining lateral variations in heat flow as a function of position on the Moon. It is possible that such measurements will be obtained by Lunar Observer. These measurements combined with absolute measurements at a few carefully chosen surface sites could result in a very precise estimate of the global heat flow.

Magnetometry

For accurate magnetic measurements at the surface, an oriented three-axis magnetometer with power supply and communication capability must be deployed. We recommend that magnetometers be emplaced at a minimum of 4 sites at a range of latitudes in conjunction with the deployment of other geophysical instruments. For the purpose of investigating crustal magnetization, some of these sites should be chosen to coincide with surface locations of large magnetic anomalies seen from orbit. To apply the surface measurements to deep magnetic sounding, an additional magnetometer in lunar orbit is required. The orbital instrument would measure the incident solar wind magnetic field.

For deep sounding studies (e.g., core detection), a major problem encountered by the Apollo magnetometers was gain degradation and calibration differences between magnetometers. For these studies, therefore, calibration and accuracy requirements are greater than for the Apollo instruments. Periodic calibration checks during the operation of these instruments will also be required.

For the purpose of investigating regional electrical conductivity anomalies, analogous to those found at the Apollo 15 and Lunakhod 2 sites, portable magnetometers carried from site to site on piloted or automated rovers may be employed. However, the use of surface magnetometers to detect regional conductivity anomalies should be studied further using low-altitude orbital data prior to undertaking a large-scale surface effort. As always, magnetic measurements must be obtained at some distance from metallic vehicles or equipment that generate significant magnetic fields.

Atmospheric Monitoring

To understand the dynamics of the lunar atmosphere and to determine its composition unambiguously, an array of sensors must be placed at different latitudes. At a minimum, three stations could be deployed, one at the equator, one at a mid-latitude, and one at a pole. Installation of two additional stations toward the other pole would test for symmetry of global atmospheric patterns. Each station should have instruments similar to LACE and SIDE, and one station, perhaps located at the lunar base, should have a full complement of atmospheric and plasma instruments comparable to or better than the Apollo instruments.

The minimum experiment package for a single station would include a neutral mass spectrometer and an ion mass spectrometer. Detection capabilities should be similar to or better than those of Apollo instruments, and they should be able to operate during daytime on the Moon. In addition to global-scale studies, specific investigations of probable sources of outgassing are of special interest. For this reason, some sites should be chosen near shallow moonquake epicenters and near surface features where transient phenomena have been reported (e.g., Aristarchus).

Finally, it should be emphasized that the mass of the natural atmosphere of the Moon is only a few tons. An Apollo-type piloted landing adds a comparable mass of exhaust products to the atmosphere that takes several months to dissipate. Hence, the natural lunar atmosphere must be studied prior to the time when manned landings will take place regularly.

External Plasma Monitoring

Solar wind spectrometers should be deployed at a range of latitudes in order to study the overall interaction of the Moon with the solar wind. In addition, it is desirable to locate some of these spectrometers at sites of strong local magnetic fields in order to evaluate the ability of strong anomalies to deflect the ion bombardment. Such an evaluation is needed to establish the surface and regolith properties that are dependent on solar wind ion implantation, as discussed above.

Deployment Options

Engineering, efficiency, and cost considerations are of primary importance in selecting the appropriate means for deployment of geophysical instruments on the lunar surface. This deployment can be accomplished in principle via (i) surface penetrators; (ii) soft landers; (iii) automated rovers released on the surface from a lunar base or landing vehicle; and/or (iv) direct human emplacement (Table IV-1).

For several reasons, it is questionable whether penetrators provide an adequate deployment option. A simple penetrator with no attitude control or thrusting capability would impact the surface at near-orbital velocity (about 1.7 km/s). It is uncertain whether sensitive geophysical instruments can be designed to withstand such an impact. In addition, a simple penetrator may not be able to carry a long-term power source such as an RTG or solar cells; if not, then the lifetime of the station would probably be limited by the battery supply to a period of the order of weeks, drastically less than the needed period of years. Although penetrators would automatically deploy seismometers and heat flow probes at the depth of burial, other instruments such as atmospheric monitors and magnetometers, as well as communications devices, must be deployed at the surface, probably on a penetrator afterbody that separates on impact. It is uncertain whether surface deployment of sensitive instruments by penetrator is feasible.

Soft landers represent a more realistic (but more expensive) option. In addition to attitude control, communication, and thrusting capability, these landers would need to be able to effectively deploy the instrument and power supply. In many cases, accurate orientation and balancing of instruments such as magnetometers and three-axis seismometers is necessary. In order to deploy seismometers and heat flow probes beneath the surface, a drilling capability is also required. In the case of the Apollo seismometers, a significant source of noise was vibration caused by thermal expansion and escape of fluids from nearby landing vehicles and equipment. Consequently, it is desirable for the landing vehicle to leave the area after deployment; this implies

Table IV-1. METHODS FOR DEPLOYING GEOPHYSICAL INSTRUMENTS

Deployment Method	Advantages	Disadvantages
Penetrators	Inexpensive Global access Good coupling of seismometer to surface	Lifetime short? Survivability Instrument alignment difficult
Soft Landers	Surface emplacement feasible Long-lived power sources	Several costly spacecraft needed Coring required Alignment possible?
Rovers	Surface emplacement feasible Moderate expense Long-lived power sources	Long-traverse range needed Coring required Global access?
Humans	Ease of emplacement Ease of alignment Possible repair of instruments Long-lived power sources	Expensive Life-support needed Protection from radiation Global access?

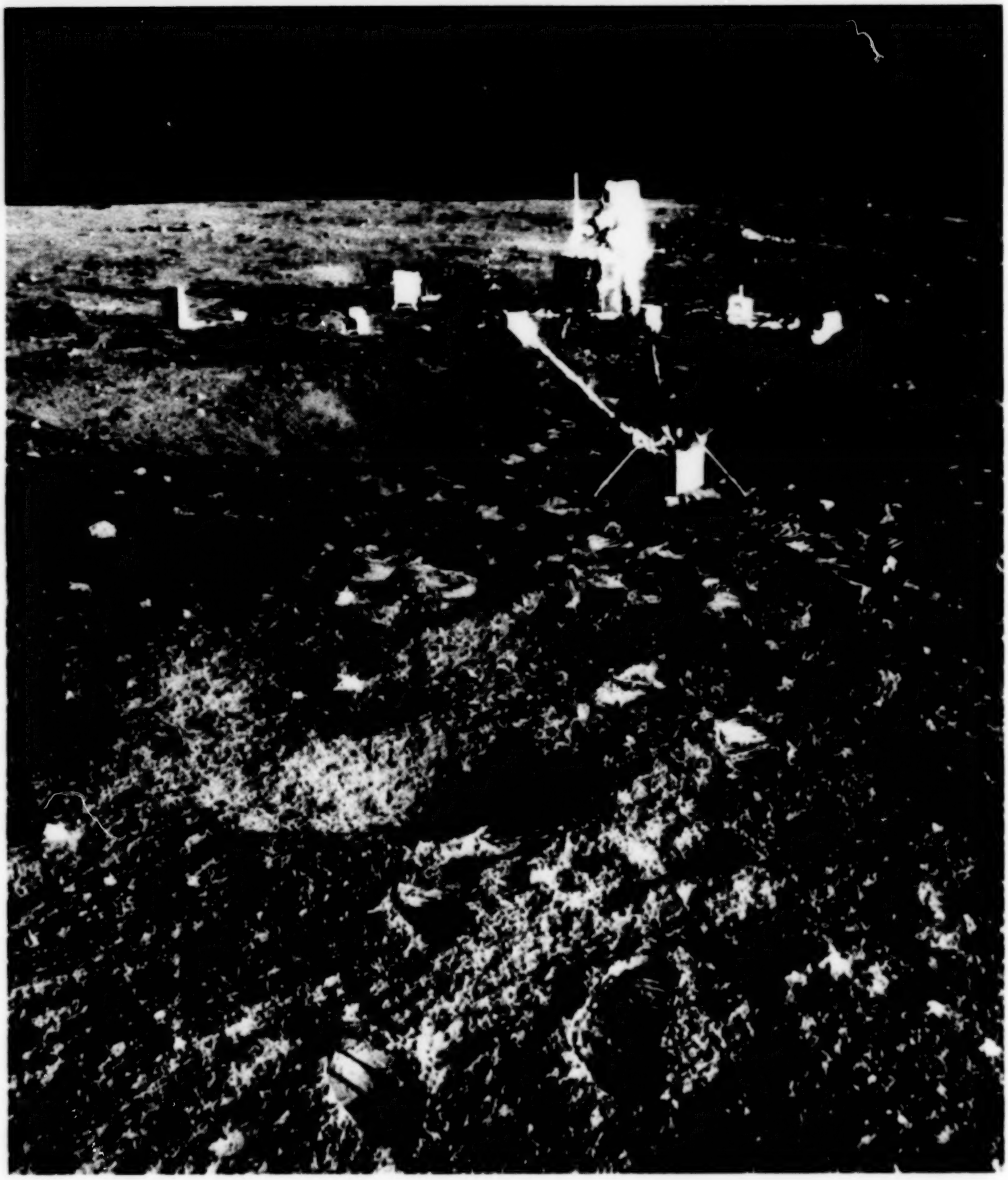


Figure IV-4. A proven way to deploy geophysical instruments is to use astronauts. An Apollo 12 crew member is shown setting up the ALSEP (Apollo Lunar Surface Experiment Package) central station, which contains data processing and transmission facilities. The passive seismic station is to the right, and the magnetometer is in the foreground.

either lateral mobility or an ability to thrust away from the immediate vicinity. If the lander returns to orbit, then it could be refitted with new instruments and reused. Otherwise, the lander could be designed to impact not far from the deployed station thereby providing a useful seismic data point (one whose event time, energy, and location are known). These various requirements mean that the soft lander would be a fairly sophisticated spacecraft, implying a higher cost than for a simple penetrator. Thus a considerable development and testing effort may be needed. However, the quality and time span of the resulting geophysical measurements is likely to be much greater than would be acquired by penetrator-deployed instruments.

If deployment of sensitive geophysical instruments via soft landers does not occur prior to resumption of manned landings, then the network may be established by automated rover or piloted expeditions from established bases or outposts. Because automated rover expeditions and piloted sorties will probably be required for other purposes such as geological exploration, these same expeditions could be designed to deploy geophysical instruments. In the case of deployment by astronauts, the method of emplacement could be similar to that for the Apollo instruments (Fig. IV-4).

Because initial activities presumably will be confined to the near vicinity of a base, the first network to be established will probably be regional, covering a surface area of hundreds of kilometers around the base. However, as exploration continues, short-hop manned landings at other sites around the Moon will occur, providing the opportunity for deployment of an increasing number of high-quality geophysical instruments.

We recommend that all four major deployment options (penetrators, soft landers, automated rovers, and manned deployment) be studied further to determine the most effective role(s) of each in allowing improved global-scale and regional geophysical measurements. Each method of deployment has its own set of problems to be resolved.

V. RECONNAISSANCE MISSIONS

To decipher the record of planetary evolution in the lunar crust, it will be necessary to examine rocks in their natural environment and deduce the nature of rock units and their relationship to one another. However, detailed field studies must be preceded by more fundamental investigations. For purposes of discussion, we refer to such broad-brush studies as reconnaissance missions. The goals of geologic reconnaissance are to provide an admittedly incomplete, but broad characterization of the geologic features and processes on a planetary body. For example, in orbital photographs of the Moon, geologists have identified areas where mare surfaces are sparsely cratered. The low density of impact craters implies that the surface is relatively young. It is of great interest to obtain samples of these youngest volcanic rocks and determine their ages radiometrically. The samples could be collected by simple, automated vehicles making no detailed field observations. The petrologic and chemical composition of the samples would also be determined, of course, but the central question addressed by such a mission would be simple: how old are the youngest lava flows on the Moon? Such a reconnaissance mission paves the way for more detailed studies.

Reconnaissance missions should not be confused with "precursor" missions, i.e., missions that obtain some type of information that is required prior to the establishment of lunar base. Although reconnaissance logically precedes detailed field study in a given locality, it need not be completed everywhere on the Moon before detailed studies can begin. We envisage reconnaissance missions as a continuing, integral part of the scientific study of the Moon before, during, and after a permanent lunar base is established.

AUTOMATED IN SITU ANALYSES

One way of doing reconnaissance studies of the Moon is to land vehicles to perform in situ analyses on the surface. The Surveyor spacecraft did this during the 1960s on the Moon, the Viking landers analyzed two sites on Mars, and the Soviet Venera and Vega spacecraft studied sites on Venus. In situ experiments are crucial in studying time-dependent phenomena and in making measurements of undisturbed rock and soil in environments difficult or impossible to reproduce in the laboratory (e.g., the lunar vacuum and radiation environment). Direct in situ measurements are the only reliable way to acquire detailed engineering data on the geotechnical properties of the lunar surface.

We propose the use of semiautonomous rovers. Such vehicles could traverse long distances on the Moon, performing chemical analyses and mapping the mineralogy of rock exposures with visual and near-infrared spectrometer. Each rover would obtain geotechnical data on soil and subsurface properties and could investigate potential ore deposits. Their key virtue is their ability to obtain data over large distances, which stationary landers such as Surveyor and Viking could not do. Experience with the Soviet Lunakhod series (Vinogradov, 1971) suggests that the potential of such vehicles to obtain both science and engineering data has yet to be realized. The use of rover reconnaissance missions could be a cost-effective way of planning more detailed investigations or surface operations.

A rover would need to have a total range of hundreds of kilometers and be capable of operating without constant supervision. It would have to carry a high-resolution color television camera, a visual and infrared mapping spectrometer, X-ray and gamma-ray spectrometers, active seismometers, magnetometers, and devices to measure the mechanical properties of soil. It would need to have high mobility to avoid hazards. It could use a chassis based on the Apollo LRV and many of the same instruments as the robotic field geologist described by Spudis and Taylor (1988) and in a later chapter of this report.

AUTOMATED SAMPLE RETURNS

Value of Returning Samples

Experience with terrestrial, lunar, and meteorite samples demonstrates the importance of returning samples to Earth. Analyses of chemical and isotopic compositions, mineralogy, rock textures, and physical properties are crucial to unraveling the record stored in planetary samples. Samples are also important to resource exploration; for example, the existence of potential ore deposits such as volatile-rich areas identified from orbit would have to be verified and quantified; moreover, the specific mineral phases that carry the volatile components could only be characterized through analysis of returned samples. As described above, in situ measurements can be made by instruments carried on spacecraft, but for many purposes there are clear advantages in returning samples to laboratories on Earth. These advantages have been articulated by COMPLEX (1978) and by LAPST (1985) and are summarized here.

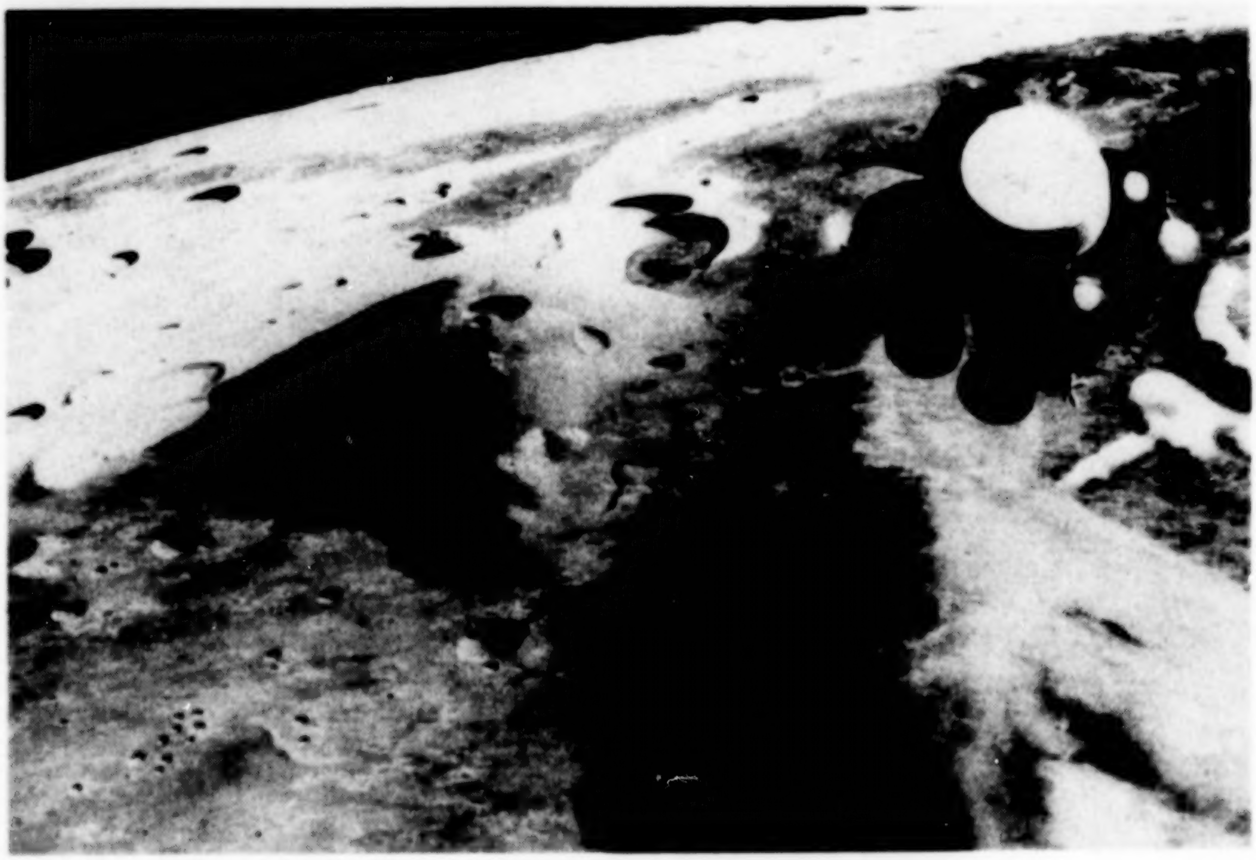


Figure V-1. Automated sample-return missions could address many important problems in lunar science. This NASA painting (by Patrick Rawlings) depicts the ascent of an automated spacecraft returning samples of the Gruithuisen Domes, which might be volcanic mountains composed of lava flows exceptionally rich in SiO_2.

Table V-1. SPECIFICATIONS FOR AN AUTOMATED SPACECRAFT TO EMPLACE GEOPHYSICAL INSTRUMENTS AND RETURN SAMPLES FROM THE LUNAR SURFACE[a].

System	Capability
Geophysical payload to surface	50 kg
Return sample payload	2.1 kg
Navigation	Land within 1 km of selected area
Sampling devices	
rake	rake 10 m^2, obtain rocks 1-4 cm
scoop	obtain 200 g (100 cm^3) bulk regolith
core	drill 2-cm dia. core 1.5 m deep
Sample storage facilities	Store and secure samples in return vehicle
Deployment devices	
seismometer	bury 1 m and balance
heat flow probe	emplace in drill core hole
magnetometer	emplace and orient
Power for instruments	on spacecraft; TBD

[a] Sample return missions need not be combined with geophysical missions.

1) Many types of analyses are too complicated to be done remotely. Age determinations by the Sm-Nd method, for example, require complicated mineralogical and chemical separations to be done in a clean room, followed by analysis in a bulky mass spectrometer.

2) Laboratory equipment will always have better resolution and precision than flight instruments because of the long time required for flight preparation and because of mass and power requirements.

3) Returned samples become resources that can be used for many years. As we learn more, new experiments can be designed and new measurements made on the samples. Similarly, as analytical techniques improve and new types of analytical devices are invented, they can be tested on and ultimately applied to curated samples.

Here we consider the problem of returning samples to Earth for study in terrestrial laboratories. Samples can also be returned to an advanced lunar base for preliminary study there (see chapter VII) to identify the most scientifically promising materials for return to Earth.

Vehicle capabilities

We envisage sample-return vehicles as being operationally much like the Luna spacecraft that returned samples to Earth from three localities on the Moon. They must be capable of collecting both rake and bulk regolith samples (Table V-1). An artist's concept of such a spacecraft is shown in Figure V-1. Reconnaissance could also be done by humans, in which case we envisage excursions much like those of the early Apollo missions.

Rake samples

A tremendous amount of useful data was obtained by studying the walnut-sized rocks collected during the Apollo 15, 16, and 17 missions by pulling a rake through the lunar regolith. The rake collected samples larger than 1 cm, which are large enough to allow mineralogical, chemical, and isotopic studies. From each landing site for which we propose reconnaissance sample returns, about 100 walnut-sized samples should be collected. This would assure a statistically reasonable sampling of the rocks present. On the basis of the size distributions of rocks in the Apollo rake samples, Dr. Alan Binder has estimated that on average, a spacecraft would have to rake 5 m^2 to obtain 100 samples 1-4 cm in size. The samples would weigh about 1 kg. To ensure collecting 100 samples, the lander ought to be capable of raking 10 m^2.

Regolith samples

Some regolith would be contained in the rake sample. This material would not necessarily represent bulk regolith because friable rake samples will break up during sampling and transport to Earth. We need to obtain a bulk regolith sample to fully characterize the site (which serves as ground truth for orbital geochemical data); a 1000-g sample would probably serve this purpose. To understand the regolith stratigraphy at the site, a core sample should also be taken. A core 2-cm in diameter and 150 cm long taken in regolith that has a density of 2 g/cm^3 would have a mass of 900 g. It is probably necessary to obtain both bulk regolith and core samples, but this needs to be studied further. Other types of regolith samples have also been proposed. For example, to collect a sample of undisturbed topsoil, a robotic arm could release a liquid epoxy onto the surface. The epoxy would penetrate the porous regolith to a depth of about 5 cm and cover an area of about 5 x 5 cm. When hardened, the liquid would form a brick-like material containing an undisturbed sample of the uppermost regolith. Ideas like this require further study to assess their scientific value and, if found to be necessary, assess the engineering implications.

This sampling strategy results in a total of 1900 g of regolith being collected. Combined with the 1 kg of rake samples, the return spacecraft would have to be capable of returning a total payload of 2.1 kg. We envisage that the spacecraft would be almost entirely autonomous. It would be preprogrammed to collect the samples, store them, and then return to Earth. It could also carry geophysical equipment and deploy them after collecting samples; whether combining sample-return and geophysical missions is cost effective or scientifically desirable needs to be evaluated.

Reconnaissance Sample-Return Missions

A series of relatively simple sample return missions may be planned for the geologic reconnaissance of the Moon. These missions are not necessarily precursor missions, as we envision the need for reconnaissance before, during, and after base establishment. A series of landing sites can be identified from the global remote sensing data returned by LO and other possible orbital precursor missions from which a Luna-type sample return will provide some first-order scientific information and guide the detailed planning of future geologic field work.

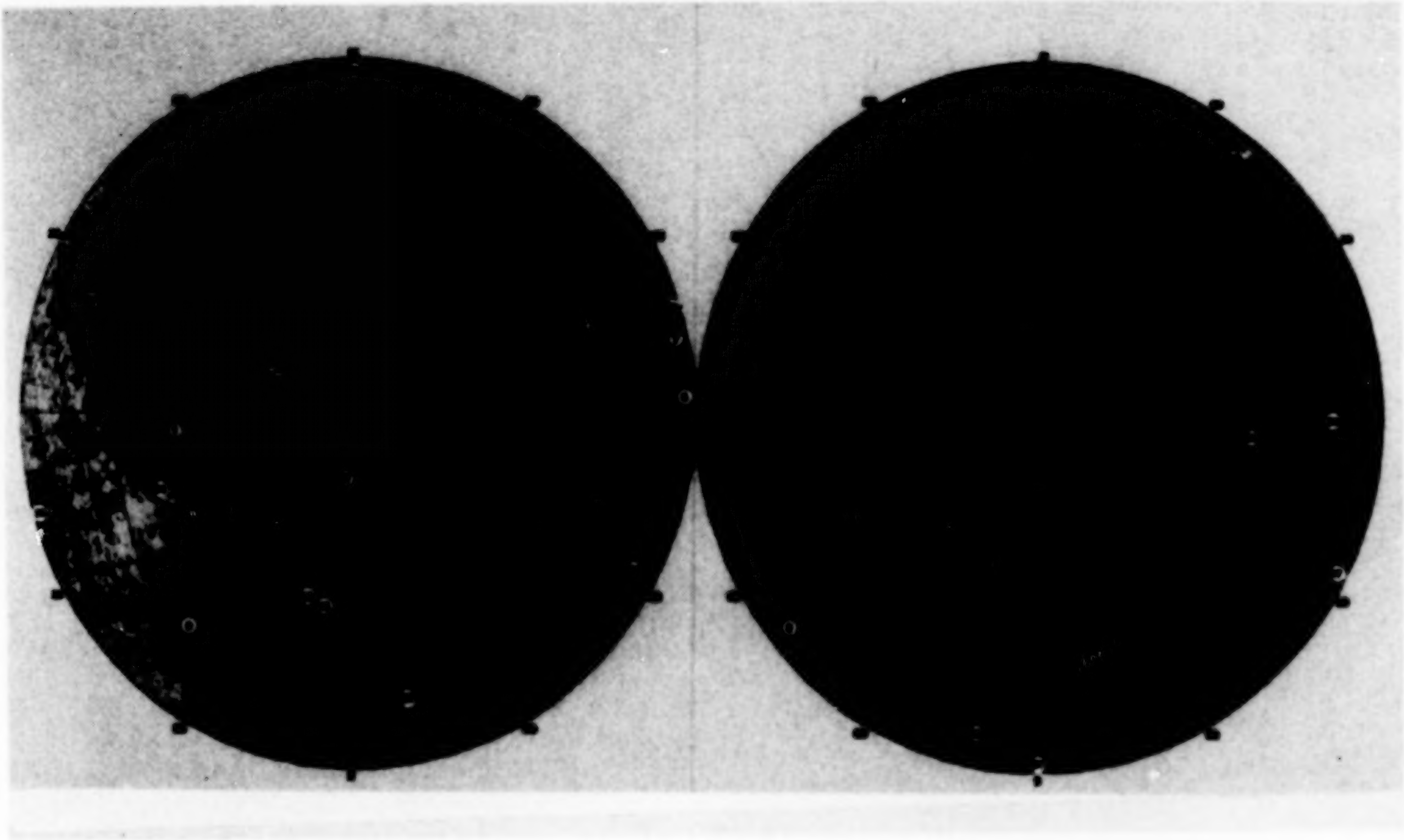


Figure V-2. Map of the Moon (equal-area projection) showing the locations of recommended sites for reconnaissance sample-return missions (numbers 1-31; see Table V-2) and for detailed study and sample return (numbers 32-59; see Table VI-2).

Table V-2. Examples of geologic reconnaissance sites where objectives can be accomplished by simple, unmanned sample returners (after Ryder et al., 1989)

Target	Objectives	Landing Point	Comments
Maria	Characterize diverse mare basalts in terms of age and composition. Determine boundary conditions on lunar thermal history; when did mare volcanism start and stop? Calibrate crater densities with isotopic ages. Determine chemical differences between near and far side maria. Determine lateral and vertical heterogeneity of lunar mantle.	1. In Flamsteed 3° S, 44° E	Surveyor 1 shows thin regolith; age about 1 Ga
		2. Near Lichtenberg 32° N, 67° E	Basalts embay rayed crater; age about 1 Ga
		3. Tsiolkovsky 20° E, 130° S	Apollo 11 composition and age
		4. Mare Ingenii 36° S, 165° E	Reiner Gamma-type swirls overlie basalts
		5. Mare Moscoviense 28° N, 148° E	Typical far side mare fill
		6. Mare Smythii 3° N, 90° E	High-Ti, very young (<2 Ga)
		7. Mare Marginis 12° N, 90° E	Young (<2.5 Ga); high Th
		8. Mare Australe 38° S, 91° E	Old mare covered by Imbrian age light plains
		9. Schickard 55° E, 45° S	Old maria covered by Orientale light plains
		10. Imbrium flows 29° N, 29° W	Young (1-2 Ga); high-Ti and KREEP-rich
		11. Mare Serenitatis 20° N, 20° E	Spectral standard, near major age (I-E) boundary
Crater Melt Sheets	Determine melt compositions for crater target. Determine projectile signatures. Isotopic ages for crater events to calibrate relative time scale for Moon and other planets. Determine melt homogeneity and clast provenance.	12. Copernicus 10° N, 20° E	Major stratigraphic horizon, complex target
		13. Eratosthenes 14° N, 12° E	Major stratigraphic horizon
		14. King 5° N, 121° E	Farside crust, very young
		15. Tycho 43° S, 10° E	Young major crater; complex rock types in target
		16. Giordano Bruno 36° N, 103° E	Youngest large crater on Moon
Basin Melt Sheets	Determine melt composition as a sample of the crustal average. Determine lateral heterogeneity of lunar crust. Isotopic age of basin impacts to calibrate geologic time scale. Samples of crustal rock types as clasts within basin melts. Determine projectile signatures for ancient large impacts	17. Orientale 25° S, 96° W	Youngest multi-ring basin on the Moon
		18. Humboldtianum 55° N, 77° E	Interesting "middle-age" basin on NE limb
		19. Schrödinger 74° S, 125° E	Young, 2-ring basin near south pole

Target	Objectives	Landing Point	Comments
Highlands	Characterize chemistry and petrology of a variety of highlands areas. Determine magmatic and impact events in highlands evolution. Sample anomalous regions to determine differences with average highlands. Isotopic dates for magmatic events in highlands history. Address thermal evolution, cratering history	20. Near Mutus 66° S, 30° E	"Average" ancient near side highlands
		21. Near Lebedinsky 10° N, 165° W	"Average" ancient far side highlands
		22. Van De Graaf 26° S, 170° E	KREEPy basalts or Mg-suite
		23. Ptolemaeus 10° S, 12° W	KREEPy basalts or Mg-suite
		24. Hertzsprung floor 4° S, 124° W	Mg-suite pluton (?)
		25. West of Tsander 7° N, 153° W	Mafic ferroan rocks or ancient mare basalts
		26. Gruithuisen Gamma 36° N, 41° W	Spectral anomaly; age and composition
Lunar Resources	Sample and characterize sites for future resource exploitation. Assess pyroclastic deposits for volatiles, high-Al regions, and possible volatile deposits at poles. Characterize compositions and ages of resource deposits; physical processes responsible for their existence	27. Rima Bode 13° N, 4° W	Major regional pyroclastic deposit; high Ti
		28. Sulpicius Gallus 19° N, 10° E	Major regional pyroclastic deposit; high Ti
		29. Aristarchus Plateau 26° N, 51° W	Regional pyroclastic deposit; appears KREEP-rich
		30. North of Orientale 0, 110° W	Nearly pure ferroan anorthosites
		31. Permanently shadowed areas near poles at 90° N and 90° S	Sample only if LO finds evidence of water ice in polar regions

As an example, a list of currently identified sites for a series of Luna-type sample return missions is presented in Table V-2; the site locations are identified in Figure V-2. This mission series serves the most pressing reconnaissance needs. Among the problems to be addressed are the completion and characterization of the mare basalt inventory on the Moon (sites 1-11) and the calibration of the relative time scale through the sampling of crater and basin impact melt sheets (sites 12-19); these same sites also permit the determination of lateral variations in crustal compositions by using impact melts as crustal probes. The early magmatic history of the crust may be addressed by sampling regions on the Moon identified from the orbital data as being petrologically interesting (sites 20-23). In addition to science, these missions can be used to characterize the resource potential of identified prospects; such targets include regional pyroclastics, volatile-rich areas, and relatively "pure" rock types (sites 24-30).

The suggested sites shown in Table V-2 are tentative and a revised list should be prepared after global remote sensing data are obtained. In our concept of ongoing lunar geologic reconnaissance, the ability to fly simple sample-return missions should be a required element of the lunar base infrastructure. Not only do these missions provide important scientific data, but they are needed to guide future, more detailed geologic investigations to be conducted as the base is established and expanded.

Example of a Reconnaissance Sample-Return Mission

Orientale is one of the largest basins (930 km in diameter) on the Moon showing a nearly complete multiple ring structure and is likely to have excavated deep into the crust of the Moon (Fig. V-3a). The Orientale event also marks the end of the era of heavy bombardment of the Moon. The melt sheet generated as a result of this impact event retains not only an isotopic signature of the absolute age of the basin, but also most likely represents the product of total melting of the target and hence the average chemical composition of the crust in this region. Stratigraphic and crater-count evidence show that the Orientale basin is post-Imbrium in age (< 3.85 b.y.) but is older than the mare basalt flows near the Apollo 11 site, suggesting that the Orientale impact occurred at about 3.8 b.y. ago. An absolute age obtained from a melt rock formed by the Orientale impact will not only date the probable end of the heavy bombardment but will also fine tune the calibration of crater-count dating, especially on the far side of the Moon. The average crustal composition of the far side of the Moon is inferred only from orbital data; sampling of Orientale impact melt will provide invaluable data on the average composition of a large area of the Moon. Because the Orientale event excavated such a large volume, fragments of the lower part of the crust (if not of the uppermost mantle) may have been ejected and incorporated in breccias. Examination of Orientale ejecta may, in fact, allow us to lay hands on such deep seated rocks.

The Maunder Formation, which makes up the fissured and fractured floor materials of the Orientale basin (Fig. V-3b) and is best interpreted as impact melts, would make an excellent landing site. The central part of the basin is filled with mare basalt, to the north of which lies the Eratosthenian crater Maunder. We suggest a landing site south of the mare fill so as to stay away from possible contamination by ejecta from Maunder crater, but close enough to the mare such that some mare basalt samples may also be found in the regolith (Table V-2; site 17). This site selection maximizes the probability of obtaining impact melt rocks, minor amounts of mare basalts, and possibly some pre-basin bedrock of the Montes Rook Formation.

Once the spacecraft landed, a robotic arm would automatically take a scoop of bulk regolith and store it. This would be followed by the collection of a kilogram of 1 - 4 cm rocks by raking. Engineering studies must be done to determine if two arms are needed or if the ends can be changed during the mission to obtain both scoops of regolith and rake samples. Finally, the core would be drilled and stowed. (The precise way in which the core is obtained requires research.) Before returning to the Earth with its valuable cargo, the spacecraft could deploy several instruments such as a seismometer and heat-flow probe, as described in Chapter IV, but the cost effectiveness of combining sample-return and geophysical missions must be determined.

PRECURSOR PRISTINE SAMPLES AND ENVIRONMENTAL MONITORS

The lunar environment is uniquely suited to many types of scientific investigations, such as astronomy (Burns and Wendell, 1988). However, the environment is also fragile and will be altered by large-scale surface operations associated with a lunar base. In addition to continuously monitoring the lunar environment (e.g., atmospheric composition and pressure, electron density), the surface should be sampled and characterized thoroughly before and during the establishment of a lunar base. One possibility is to obtain core samples from around the Moon and store them in sealed containers for future reference. Detailed in situ measurements on, for example, the concentrations of volatiles with depth in the regolith also need to be made before significant environmental degradation takes place. How many contingency samples need to be obtained requires further study.

The lunar atmosphere will be altered by base or outpost operations, so mass spectrometers need to be operated continuously. Besides spotting activities that potentially cause irreversible changes in the environment, these instruments will be useful in monitoring natural releases of gases, such as those released by tectonic activity. Also, monitoring the buildup and dissipation of an artificial atmosphere on the Moon will be an interesting scientific experiment in itself.

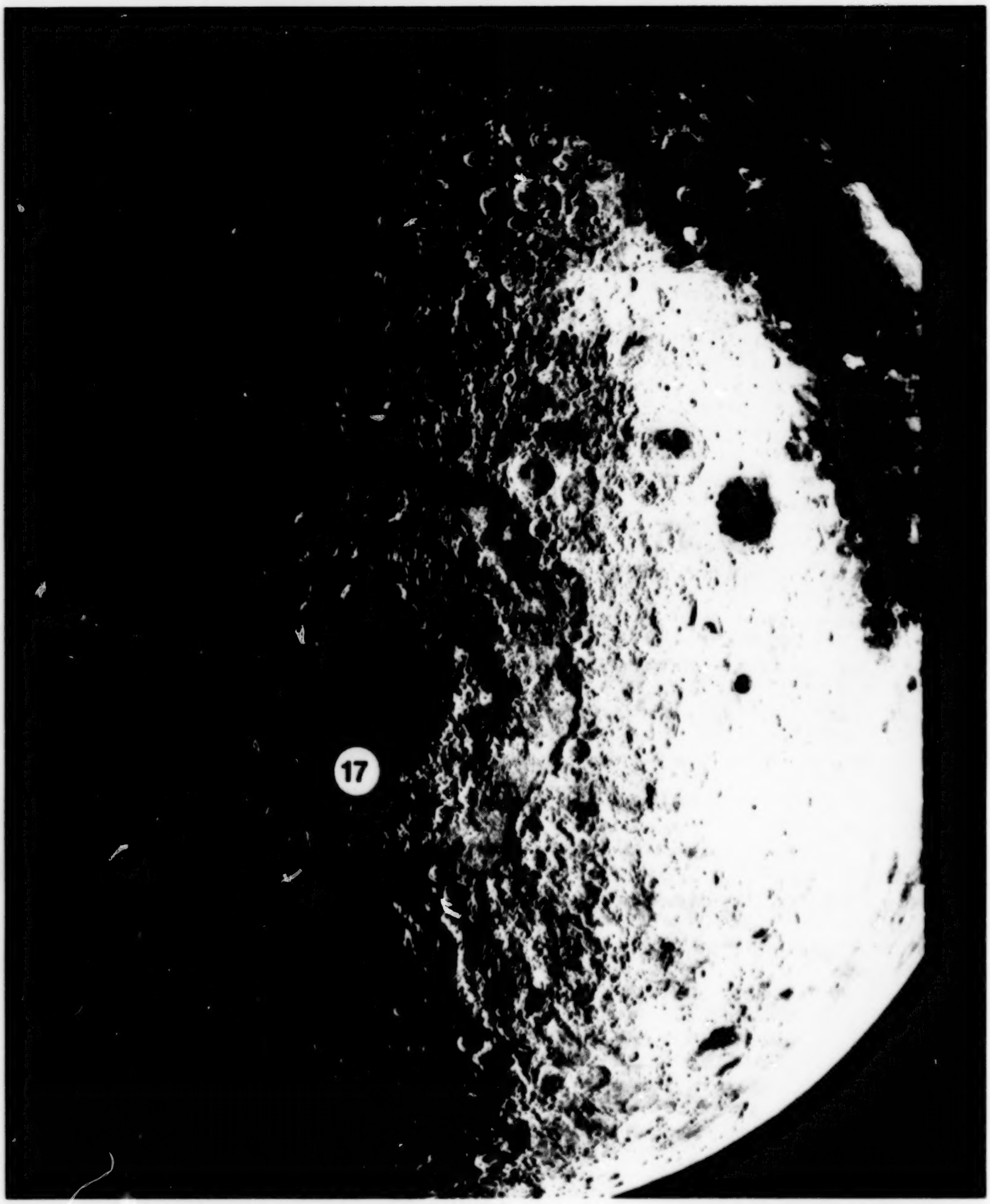


Figure V-3a. Samples from Orientale, the youngest multiringed basin on the Moon, would provide information about the age of the event that formed the basin, which marks the end of the heavy bombardment of the Moon. Samples of the impact melt sheet would also provide data about the composition of the crust in this region. Number refers to the site listed in Table V-2. Lunar Orbiter photo IV-187M.

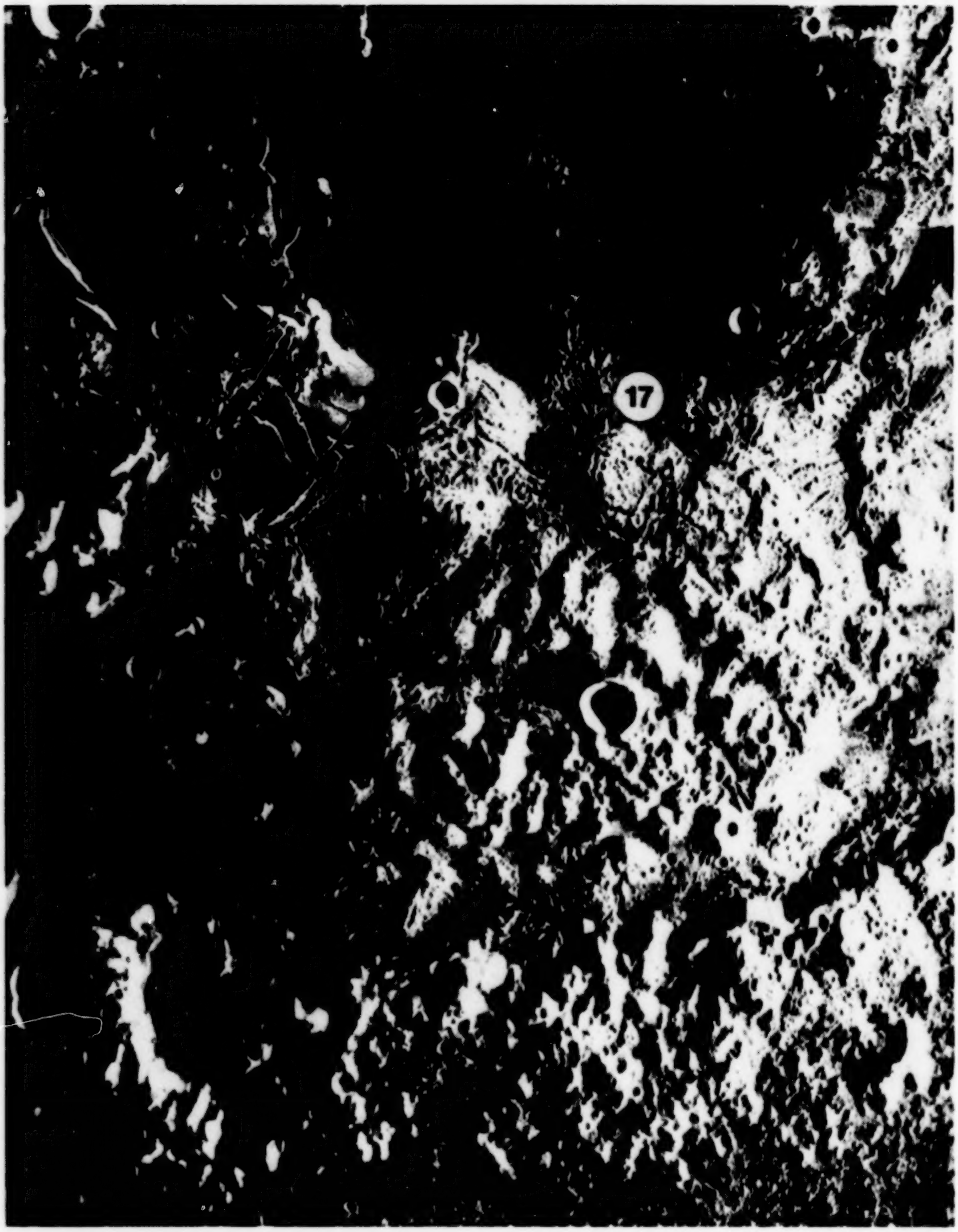


Figure V-3b. High resolution photograph of suggested landing site on the Maunder Formation inside the Orientale basin. This site would allow collection of impact melt (light-colored material next to the number) and probably some mare basalt (dark material nearby, to the north) thrown to the landing site by impacts on the mare.

VI. GEOSCIENCE INVESTIGATIONS FROM A LUNAR BASE

Geoscience will flourish when a lunar base is established. Even an initial, modest outpost will provide unprecedented opportunities for the scientific investigation of the Moon. As the base expands in capability and personnel, astonishing opportunities for understanding the Moon and planets will open up, and the questions posed in Chapter II will be addressed in more detail than ever possible before. This chapter outlines the nature of the scientific investigations that will be done early in the lunar base's development, including the geophysical studies that will be conducted at the base, and finally the types of investigations that will be possible at an advanced lunar base. Curatorial and analytical facilities are discussed in Chapter VII and the equipment needed for base operations (e.g., sampling devices, roving vehicles) are described in Chapter X.

GEOSCIENCE STUDIES EARLY IN BASE DEVELOPMENT

We assume that the time allocated to geological investigations will be limited during the construction phase of the lunar base. Nevertheless, important scientific investigations will be possible. Once that phase of activity is completed, we assume that astronauts will be able to range several tens of kilometers from the base, thereby opening up an area for research far greater than was possible during the limited-duration Apollo missions. This greater range, coupled with the continuous occupation of the base, will provide golden opportunities for understanding the Moon's geologic history.

Geoscience studies during construction of the Lunar Base

Lunar base construction will involve digging and moving regolith material to use as radiation-shielding for human habitats. Although the details of how this will be done have not been worked out, these operations will provide important information about the lunar regolith. Excavation equipment will allow astronauts to dig deep trenches in the regolith. Such excavations could address several important problems in lunar geoscience. For the first time, it will be possible to study regolith stratigraphy in place. A cross section from the surface to bedrock (3 to 8 meters in mare areas) would contain a record of the Sun's evolution during the past 3 to 4 billion years. It would also contain detailed information on how the powdery regolith materials formed from solid rock, the efficacy of horizontal and vertical mixing, and the variation of precious volatile gases with depth. This study would aid our understanding of remote-sensing data by providing information about how the composition of the regolith relates to the bedrock beneath. Finally, the interface of the regolith with the bedrock is of great interest. We do not know the extent to which the contact is gradational or sharp, or how much bedrock is preserved intact (which might be important for planning expansion of the base).

We assume that astronauts will spend some time exploring the vicinity of the base, much as Apollo crews did. Such sampling will not solve all lunar science questions, but will provide initial characterization of the site and permit planning of future exploration of the base vicinity. Furthermore, the results of sampling near the base actually yields regional information when combined with remote sensing data obtained from lunar orbit.

Sample collection is a prime geoscience activity. No matter where the lunar base is located, a variety of samples will be collected to characterize the local geological environment and detailed field work will be done to understand the local geology as completely as possible. It will be especially important to study bedrock outcrops exposed, for example, within crater walls. A major advantage of lunar base investigations over those conducted by Apollo will be the ability to spend large amounts of time at selected areas. For example, during the Apollo 15 mission in 1971, a boulder at Spur crater recognized by the astronauts as interesting could not be sampled because the allotted time had expired for that station. Similar situations occurred during virtually every Apollo mission to the lunar surface. With lunar habitation facilities, not only could a whole day be spent at a single field site, it will also be possible to revisit various sites. Such a strategy is common during terrestrial geologic field work, but was not feasible during Apollo because of strict time constraints. In addition, some breccia boulders may be so complex that many weeks will be required to study them completely; thus, the capability of making extended field studies near the base must be exploited, even early in the base's evolution.

Geological studies within tens of kilometers of a Lunar Base

We here illustrate the types of geologic investigations that will be possible after a lunar base is operational by a specific example. The example chosen is a base located on the Aristarchus plateau, but we could

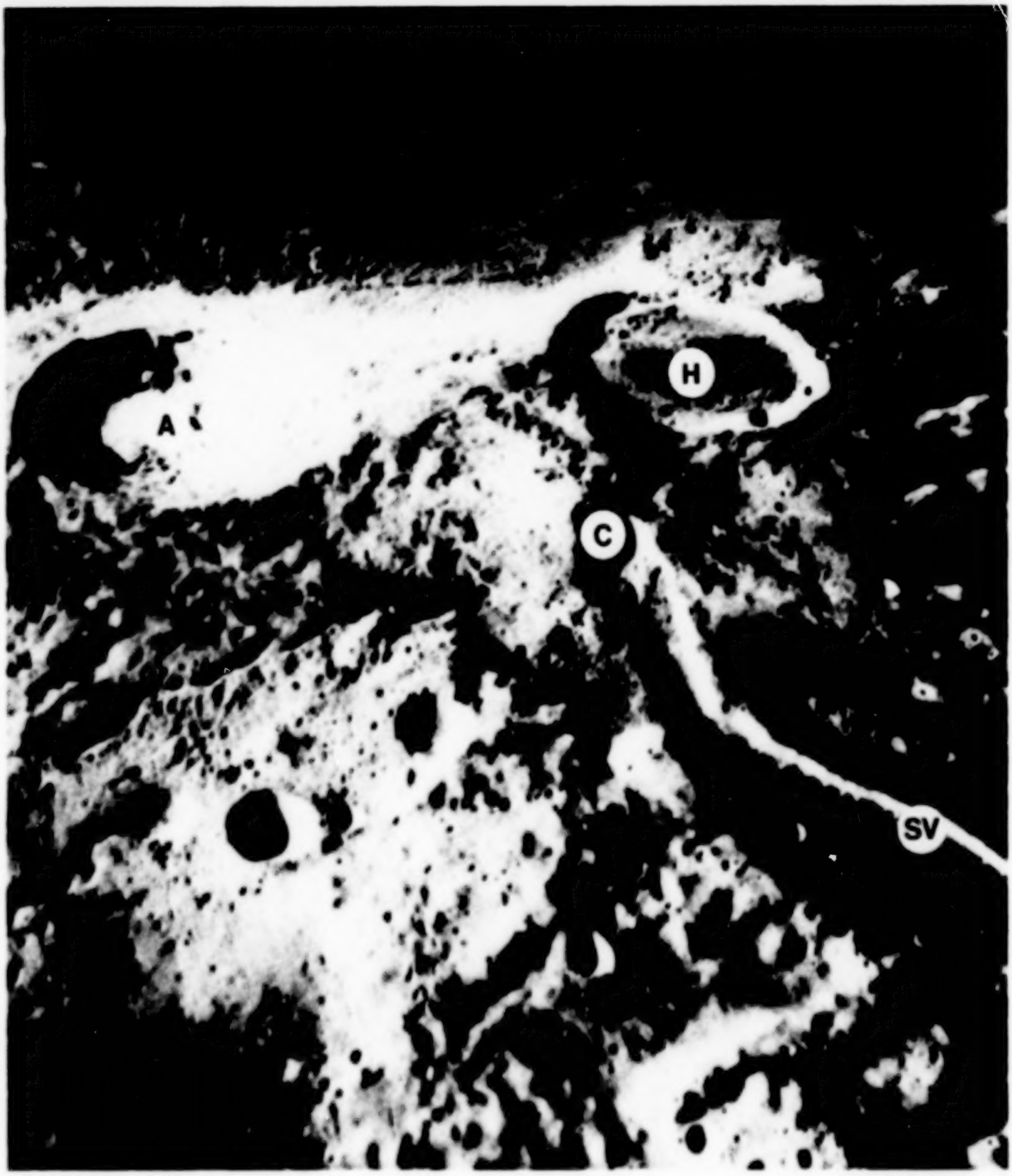


Figure VI-1. The Aristarchus plateau is one of numerous regions where detailed geologic investigations would be fruitful. Shown in this Apollo photograph (AS15-2607) are the impact craters Aristarchus (A, 42 km in diameter) and Herodotus (H), the Cobra Head (C), and Schroter's Valley (SV). Aristarchus Crater straddles the boundary between an uplifted block called the Aristarchus Plateau and mare basalts to the southwest. The crater penetrated the basalts into underlying highlands materials rich in KREEP. The Cobra Head appears to be a volcanic vent; Schroter's Valley is the channel through which the erupted lavas flowed. Pyroclastic deposits are also present.

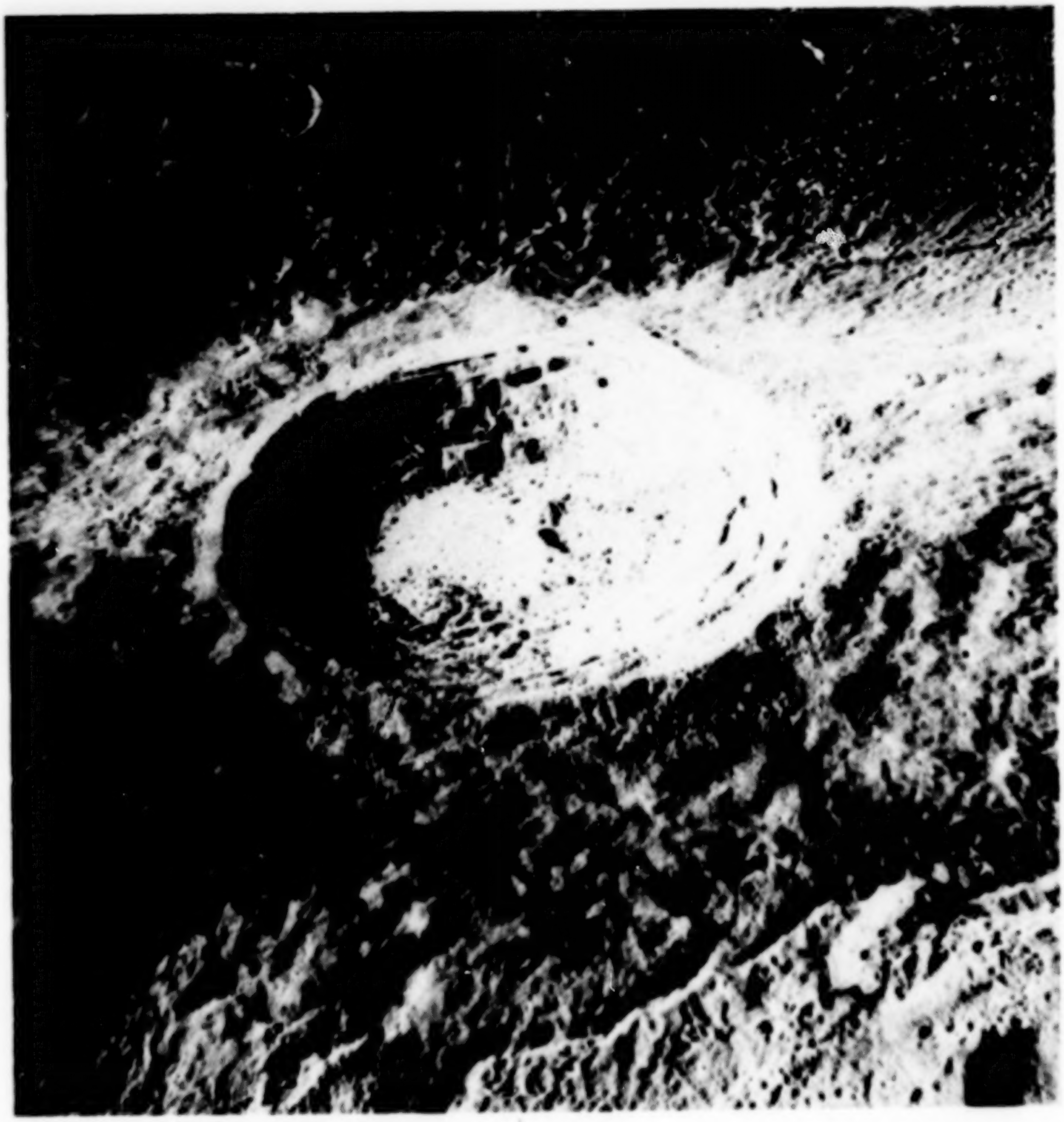


Figure VI-2. The crater Aristarchus, 42 km in diameter, is relatively young, probably less than a billion years old. Detailed study and sampling are needed of its terraced walls, central mountains, and smooth floor, which is probably composed of impact melt overlying broken, mixed, and shock rocks. Apollo photograph AS15-2609M.

have chosen numerous other localities. The decision on where to locate the lunar base will be made on many factors besides its interest to geoscientists; for example, types of resources available and ease of transportation to and from Earth.

The Aristarchus plateau

The Aristarchus region (Fig. VI-1) is located between Mare Imbrium and Oceanus Procellarum on the lunar near side. This is a complex area showing spectral, geochemical, radar, and thermal anomalies which suggest that a variety of fundamental questions in lunar geoscience may be addressed and answered from an investigation of this area. The relatively young (about 450 million years old) crater Aristarchus (42 km diameter) is situated on the boundary between the Aristarchus Plateau (an uplifted highland block) and mare basalts to the southwest (Fig. VI-1), and has penetrated a mare basalt cover to excavate a variety of highland rocks including those rich in the enigmatic material KREEP. Earth-based mapping reveals several episodes of mare volcanism in this area (including pyroclastic deposits), and one sinuous rille associated with a volcanic source vent.

Goals of Geological Investigations

We have identified six major geologic goals for the investigation of this geologically diverse region. A brief rationale for each topic is given below.

1. *Crustal Evolution of the Moon.* Mare basalt flows and pyroclastic deposits from at least three volcanic episodes at 3.6, 3.3, and 2.7 b.y. have been mapped in this region; a fourth older unit (3.75 b.y.) may be present below the others. Aristarchus crater has excavated three types of highland rocks of unknown pre-mare ages. A high thorium anomaly in the center of the crater suggests that at least one of these lithologies is KREEP-rich. Hence, a variety of highland material (_ 4.4 and 3.9-4.1 b.y. ?) may be present in the region. Investigation of this region of the Moon, therefore, will span nearly 2 b.y. of crustal history.

2. *KREEP and its emplacement.* High radioactivity and radon emanations are associated with the crater Aristarchus, indicating the presence of a significant amount of KREEP. It is not known if this KREEP is contained in breccias or occurs as volcanic basalt; both might be present. This region is, therefore, an appropriate site for a systematic investigation of the geologic setting and nature of KREEP.

3. *Eruption Mechanisms of Mare Basalts.* The presence of a volcanic vent (Cobra Head; Fig. VI-1) at the upper end of a sinuous lava rille (Schröter's Valley) and at least three units of mare basalts and pyroclastic deposits provide an opportunity to make detailed measurements of the size distribution of bombs, thicknesses and volumes of lava flows, and the selection of suitable samples for age determinations (Fig. VI-1).

4. *Regolith Stratigraphy and Facies Relationships.* Because of the small scales of operation and short exploration times by Apollo astronauts, no investigation could collect even the rudimentary data necessary for understanding lunar regolith stratigraphy and facies relationships. As noted above, excavation of the regolith to expose vertical sections, like gravel pits on the Earth, could be done during lunar base start-up operations. Additional strategically located pits would yield data regarding regolith formation, emplacement, and modification processes. Aristarchus, being a young crater, has a thin regolith on its flanks which provides an important comparative study area to older regoliths.

5. *Impact Mechanisms.* Aristarchus ejecta (Fig. VI-2) are distributed asymmetrically, which may be caused by the presence of different lithologies in different sectors of the crater target. A definitive identification of ejecta and their respective provenances is essential to fully understand the excavation process. Such a study is possible in the Aristarchus region because it is a well-preserved crater that straddles a highland and mare boundary, and is not so large as to complicate the identification of ejecta provenance. Aristarchus also presents an opportunity to study the impact-melt sheet of a complex crater. The crew could monitor an automated drilling rig (Fig. VI-3) designed to obtain a vertical section of the melt sheet and to sample the underlying brecciated rock.

6. *Block Faulting.* The Aristarchus Plateau is an approximately rectangular (170 x 220 km) elevated crustal block bounded by faults. A geophysical investigation in this region would be the first to obtain basic field data about the mechanisms of block faulting in the lunar crust.

A Case Study: Pyroclastic deposits of the Aristarchus Plateau

Here we briefly describe an example of a traverse in the Aristarchus Plateau (Fig. VI-1) over dark mantling deposits that are suspected to be glass fragments of pyroclastic origin. The Apollo 17 orange glasses are an example of pyroclastic deposits, although the deposits in the Aristarchus region appear to be different. It is possible that the regolith in this area may be made up almost entirely

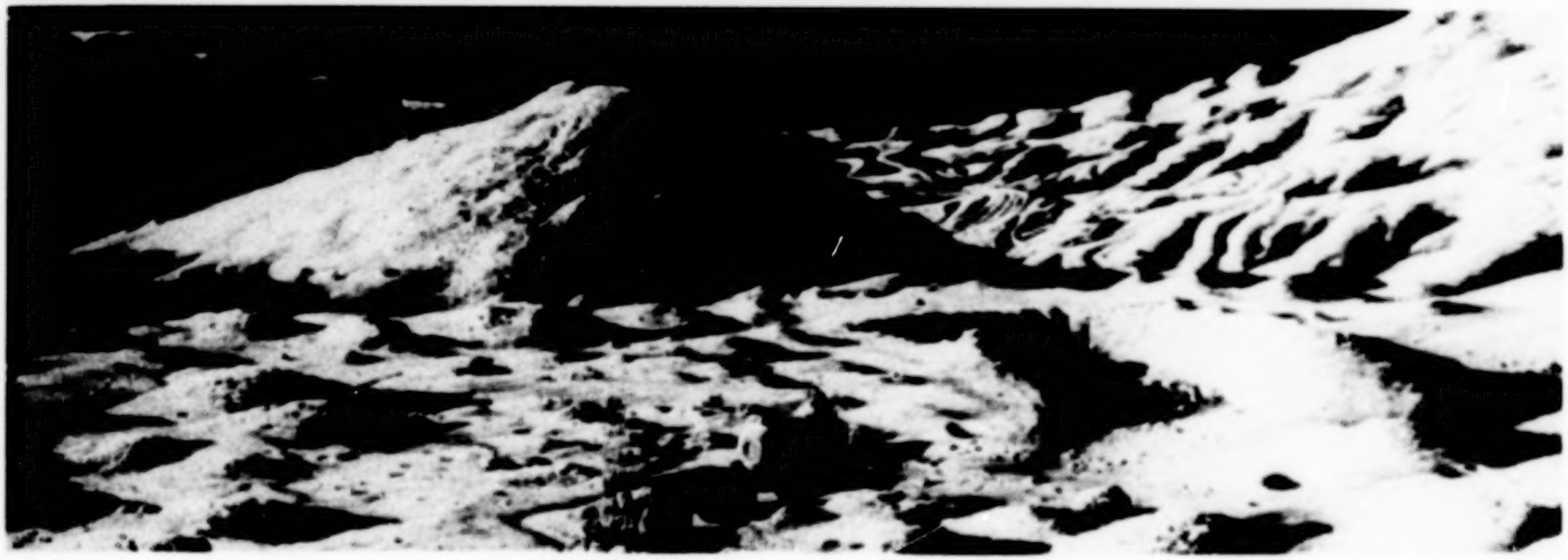


Figure VI-3. A drilling operation on the floor of Aristarchus. The core will contain valuable samples of the impact melt sheet, the composition of which represents the composition of the upper several kilometers of the lunar crust in this region. The samples will also contain information about the nature of the underlying rocks and about the cratering process. NASA painting by Patrick Rawlings.

of pyroclastic deposits. Pyroclastic glasses have been shown to be unmodified samples of magmas generated in the mantle of the Moon, to carry gas bubbles that store an inventory of volatiles as they existed in the interior of the Moon, and to provide extremely important clues to the origin and evolution of the Moon itself. Moreover, it is likely that the pyroclastic deposits in this region come from a single set of volcanic eruption(s) and that their composition is likely to be fairly uniform. This is important for construction engineers who may then rely on one method, or a limited number of simple methods, to process this material; for example, to produce fused bricks for construction. Further, both Schröter's Valley and possible lava-tubes in the area (Fig. VI-1) may be evaluated as possible abodes for future human habitation.

Specific tasks in the study of pyroclastic deposits

The specific tasks of this traverse are: a) Map and sample the pyroclastic deposits and establish the stratigraphic relations between different pyroclastic beds, and associated basalt flows if any, and estimate the volumes of pyroclastics and lavas to understand the mechanisms and processes of their origin and emplacement; and b) Conduct a geophysical traverse to obtain subsurface information of shallow level (up to ~30 m) deposits, estimate their thicknesses, and obtain depths to bedrock if possible; search for possible underground lava-tubes.

Field Area. The target of this traverse is an approximately 40 km x 40 km area adjoining and including parts of the volcanic crater/vent Cobra Head and the edge of the lava channel Schröter's Valley (Fig VI-1). In addition to these features, there are many small fresh craters, a minor rille, and a few mare ridges. Aristarchus deposits discontinuously cover the area; thus, the original depositional relationships between various pyroclastic units and/or lava flows may have been disturbed.

Mapping Surficial Deposits. The first task of the geologists will be to map the surficial material in this area; this task will include verification of the inferences drawn on the basis of remote sensing. Units will be identified, mapped , and sampled on the basis of mineralogic composition, color, size, and shape of regolith particles (most of which are expected to be of pyroclastic origin). Sub-units within the pyroclastic material could be recognized and defined on the basis of the distribution of gas bubbles, bombs, and stretched inclusions. The minimum thickness of mantling material that presumably erupted from Cobra Head is between 2 to 12 m in this area, therefore, the surficial map is likely to document the distribution of different pyroclastic deposits and their stratigraphic relations. Other vents, unrecognized from Earth-based observations, may be discovered. Parts of this area apparently are relatively undisturbed by subsequent cratering and some original volcanic stratigraphy is likely to be deciphered; such decisions can only be made in situ by geologists. If Cobra Head is indeed the vent from which the pyroclastic material and the local lava flows erupted, then a searches will be made for: systematic variations in their compositions away from Cobra Head, clues to the geometry of the vent, and inclusions of deep seated rocks (xenoliths) in the erupted material. Because high radioactivity and radon emanations are associated with Aristarchus, boulders of KREEP-rich rock types may be found and characterized.

Mapping Subsurface Units. Geophysical measurements of the area can be taken in an approximate grid pattern to obtain a shallow subsurface map of the area using broadband electromagnetic methods and active seismometry. The EM survey is simple and entails carrying two looped coils, about 1 m in diameter, and using an induced current to elicit electromagnetic responses from shallow depths. Alternatively, a rover could record the electromagnetic responses (reflections) if a fixed transmitter were set up in the region, as was done at the Apollo 17 site. In the absence of water in the lunar regolith and rocks, the dielectric constants are substantially lower than what they would have been under moist conditions; electrical resistivities of lunar material are very high. The responses would be different for pyroclastic deposits, mare basalts, and highland rocks. Therefore, analysis of reflection and refraction of electromagnetic sounding would be an appropriate technique for this mapping. The data are to be processed in real time and the results made available to the field party. These data will produce both a thickness map of the pyroclastic deposits and locations of highland rocks buried under shallow mare basalt flows or pyroclastics. The presence of any subsurface voids, such as a lava-tube, would also be detected. The combined geological and geophysical map, available on the computer screen on the rover, would provide the necessary guide to the geologists for detailed observations and sampling.

Eruption and Emplacement of Pyroclastics. No stratigraphic correlation between regolith layers, observed in drill cores, has been established at any of the Apollo landing sites. Yet pyroclastic, and possibly even ballistic, deposits should show some layering. Therefore, investigation of regolith stratigraphy will be an important task for this field study. Two trenches at right angles to each other and transverse to the observed depositional strike would be dug in the unconsolidated regolith of pyroclastic material. Unit boundaries would be traced laterally and vertically to infer the three-dimensional geometries of the deposits. Primary sedimentary structures observed in the trenches (e.g., chaotic distribution of pebbles and boulders, graded bedding, cross-bedding, nature of upper and lower contacts) together with the geometries of depositional units should reveal their modes of emplacement, which in turn would shed light on the nature of correlation among regolith and/or pyroclastic layers. Vertical profiles could be constructed from the field data, which would identify cycles or repetitive stratigraphic motifs in the regolith, if any. Parts of the pyroclastic deposits may be welded and could resemble terrestrial ignimbrites. Vertical sections through such layers and measurements of the size and fabric of clasts would reveal the mode of emplacement (e.g., ash flows or ash falls) and the eruption behavior of such layers. Orientations of regolith and pyroclastic grains with respect to the radial direction towards Cobra Head are also to be measured during this interval of the traverse. In addition, this kind of a thorough investigation of the ejecta from Aristarchus would also help in understanding theoretical and experimental models of ejecta emplacement.

Geometry of Pyroclastic Deposits. The geophysical map will determine the thickness of unconsolidated pyroclastic deposits and the regolith. Areas of minimum thickness will be the targets for trenching and drilling to determine (a) the relationship between the unconsolidated regolith and underlying bedrock, and, (b) the actual thickness of pyroclastic deposits to verify and calibrate the electromagnetic signals used to produce the subsurface map. Isopach maps of pyroclastic deposits, characteristics of their internal primary structures, and the size distributions and fabrics of erupted particles, would lead to considerably greater understanding of lunar volcanism. In addition, isopach maps of pyroclastic deposits would allow realistic estimates to be made of the reserve of such material for industrial processing.

Sampling. Representative samples are to be collected and documented from all the mapped surficial units. Samples will be selected by field geologists with a view towards understanding not only the origin of the samples but also the larger geologic context and the processes that the samples might represent and reveal. Samples will include what appears to characterize the unit; in addition, two or more samples from each unit will be collected to represent the range of variation in the material of the unit. The field geologists will decide which units appear to be most informative about processes of origin of pyroclastic deposits; for example, those with a large number of gas bubbles, or, one with inversely graded beds. A systematic sampling of a vertical profile, possibly obtained by drilling, and all lateral variations of these units will be done. Finally, any unusual materials, (e.g., exotic boulders) will be sampled.

Selecting Traverses for the Immediate Future. During the traverse, the geologists would also make observations for planning future traverses. For example, in this region it will be important to look for and document exposures of layered basalt flows and pre-mare crustal rocks. The walls of Schröter's Valley and other rilles are likely places to find basalt layers (Fig. VI-1). If seen, it will be important to measure and document the stratigraphic continuity of such layers, which could be done with photographic and sighting devices carried in the rover. The edge of the rille is also likely to have a very thin cover of regolith as was observed at the edge of Hadley Rille. Conditions would be suitable for investigating regolith dynamics because some of the soils are liable to slide down the rille as new materials are added and the angle of repose is exceeded.

GEOPHYSICAL MEASUREMENTS

Seismic network analysis at a lunar base

As discussed in Chapter IV, we propose deployment of a minimum of eight passive seismic stations spaced approximately equally over the entire lunar surface. Once established, the stations should acquire and telemeter seismic data autonomously for a period of at least ten years before requiring refurbishment. The data from each station could be radioed by direct line-of-sight or by satellite relay to an occupied base or to Earth for analysis. Data analysis at a lunar base would probably consist of seismicity monitoring and preliminary modelling of velocity and structure, periodically supplemented by more sophisticated analysis from Earth. This level of analysis, more or less continuously available for comparison with other data, will be necessary in order to form accurate models of the geophysical structure and composition of the Moon's interior.

Establishment of seismic network sites remote from a lunar base could be by piloted sortie in conjunction with other piloted scientific or operational activities. This implies a mobility capability with a one-way range of about 5000 km and a stay time for two to four persons of a week or two, although deployment of the seismic instrument itself is not likely to take more than a day or two. Such

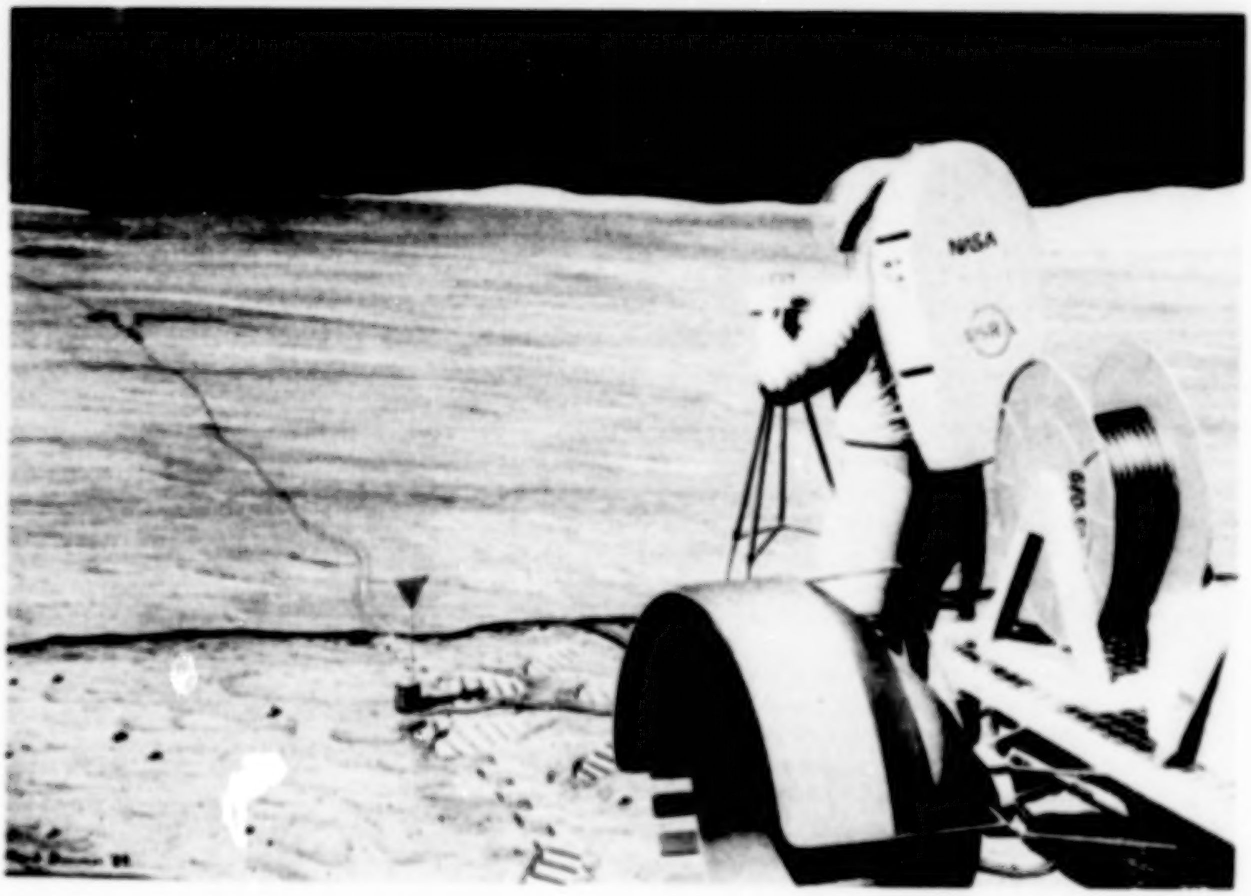


Figure VI-4. This astronaut is deploying a geophone line for active seismic measurements. Each geophone must be located precisely, so the astronaut is using a laser theodolite. Such studies will shed light on large-scale structures on the Moon, such as the nature of the rings of multiring basins. NASA painting by Mark Dowman.

installation times would be determined primarily by drilling difficulties and collateral activities. Portable drilling equipment is required.

Local base arrays of seismic instruments

The widely spaced network seismic stations will provide low resolution global information, but in order to investigate the near-surface substructure in detail, additional arrays of closely spaced instruments will be required. We propose that such arrays be established in the immediate surroundings of an occupied outpost or base. Instrument spacing will be on the order of one to several kilometers with about 10 to 15 instruments constituting the array. The synthetic aperture of this array will make it a high quality network station for monitoring natural seismicity, but its primary use will be in conjunction with active seismic sources, such as explosives. The array will also function as an environmental monitoring tool for nearby scientific activities such as the operation of astronomical instruments that may be sensitive to transient atmospheres and ground motions induced by base operations (e.g., rocket launches or mining activities). A more advanced version of this would be to have several geophone lines deployed across the surface. The geophones would be closely spaced, perhaps only 100 m apart. Such an array would permit studies of significant structural contacts, such as mare-highland boundaries (Fig. VI-4).

The operational requirements implied by this local base array are minimal, consisting of surface mobility with a range of about 25 km. This surface vehicle could be piloted or robotic (teleoperated from Earth or the base), but local piloted geologic investigations are likely in any case and the instruments could be emplaced in conjunction with these operations. The base seismic laboratory would consist of hardware to receive the telemetered data from the local (and global network) stations and the ability to store data and selectively display and analyze real-time or archived data.

Remotely fielded seismic arrays

In addition to the local and global network seismic stations, it will be desirable to field temporary arrays to remote sites on the Moon in conjunction with detailed investigations of specific phenomena such as seismic "hot spots", mascons, and transient events. The operational requirements of these "lunar science sorties" that will be mounted from a base are likely to be a combination of the requirements for the establishment of the network stations and the local seismic arrays; i.e., a long-range piloted sortie vehicle that carries a short-range surface vehicle. The remote site operations are likely to be a combination of teleoperated instrument placement and astronaut operations such as detailed geologic mapping, so the local vehicle should be capable of either type of operation mode. The seismic instruments associated with this type of investigation need only have a limited lifetime, probably measured in months, and are likely not to be worth the difficulties associated with their recovery.

Surface gravity surveys

In addition to obtaining global gravity data (see Chapter IV), it is desirable to conduct remote gravity gradient surveys on the lunar surface for such purposes as detailed investigation of mascon structures, location of subsurface lava tubes, and resource prospecting. Self-leveling gravimeters mounted on surface vehicles is the method of choice except in the most difficult terrain where back-packed instruments might be required. A typical survey might consist of a several kilometer-square grid of stations with a 100 m spacing or a line of stations across a particular structure of interest. The operational requirements would be very similar to those needed for the remote seismic sorties and the two types of measurements could be performed simultaneously. Elevation control is critical so careful topographic surveys would be needed in conjunction with gravity surveys.

Paleomagnetism and Surface-Plasma Interactions

In order to establish improved observational constraints on the origin of lunar magnetism, future work should include (i) additional orbital measurements of crustal magnetic fields such as will probably be obtained by the planned Lunar Observer spacecraft (see Chapter IV); (ii) the return of new samples, particularly from the sources of strong anomalies; and (iii) additional surface magnetic field and solar wind spectrometer measurements, especially near strong anomalies seen from orbit.

Automated rover traverses or human traverses could locate and sample specific source rocks. Targeting strong anomaly sources for sample returns (e.g., Reiner Gamma in western Oceanus Procellarum (Fig. VI-5) or the Mare Marginis swirl belt) would be especially desirable. The return of such samples could establish whether the lunar swirls represent scouring and residues produced by relatively recent impacts of cometary comae. In addition, samples obtained from these and other sites would be subjected to laboratory paleomagnetic studies for comparison with the Apollo results. Such laboratory studies might be carried out best on the Moon to

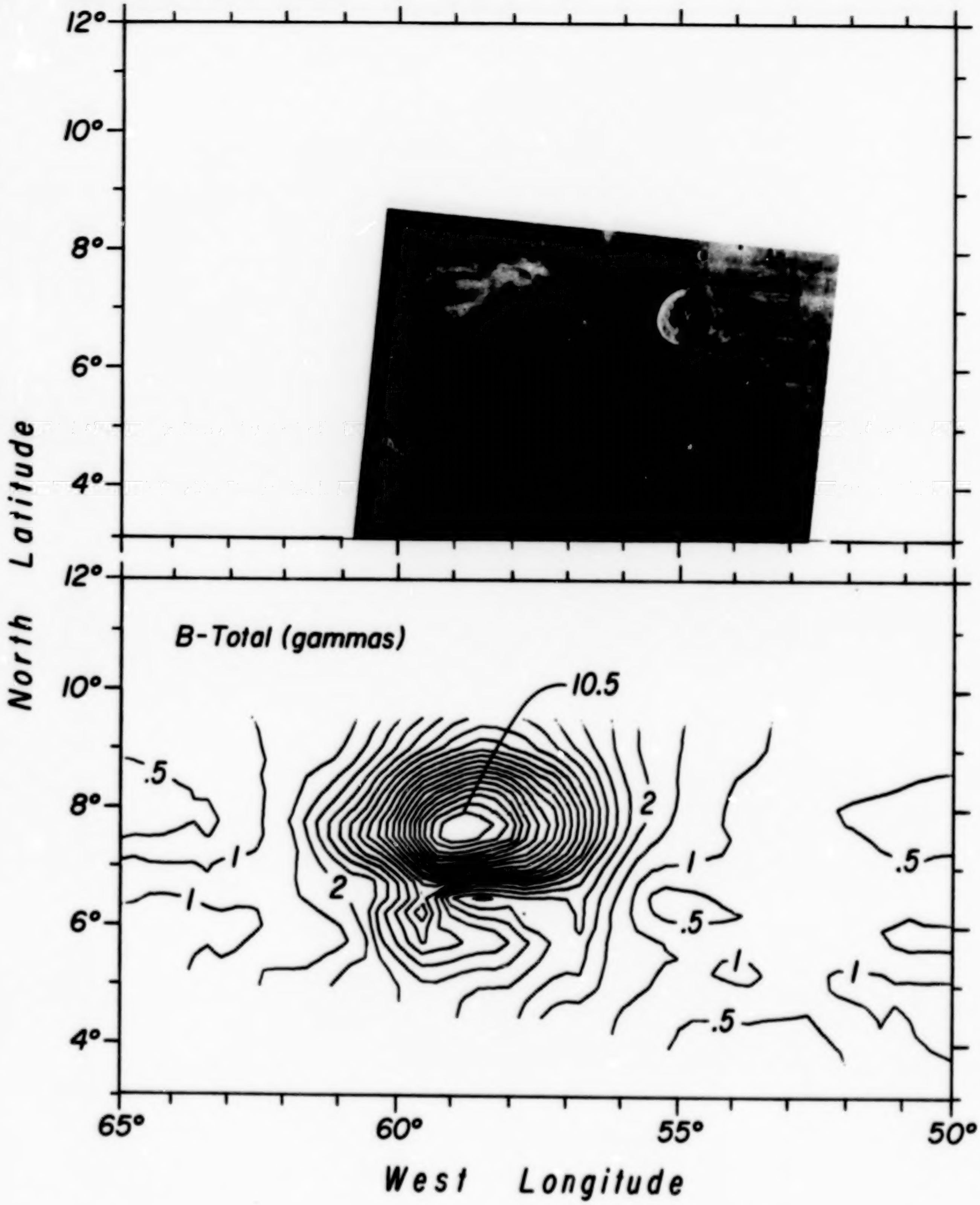


Figure VI-5. The strongest magnetic anomaly detected by the Apollo subsatellite magnetometers is correlated with Reiner Gamma, a swirl deposit of unknown origin. Return of samples could help determine how such deposits and the associated magnetic anomalies formed.

prevent contamination of the samples from the strong terrestrial magnetic field.

Surface magnetic field measurements would be useful to determine the bulk magnetization intensity of subsurface materials and to identify probable source materials for anomalies seen from orbit. In combination with orbital magnetometer measurements, surface measurements would allow the construction of more accurate models for the sources of magnetic anomalies. Simultaneous solar wind spectrometer measurements would identify those areas, if any, that are entirely shielded from the solar wind ion bombardment by locally strong crustal magnetic fields. If such areas are found to coincide only with swirl locations, then the solar wind deflection model for the origin of the swirls would be directly confirmed, implying that the ion bombardment is a necessary factor in the optical maturation with time of lunar surface materials. Such a result would have major implications for the optical maturation process of surface materials (e.g., the disappearance of crater rays with time) on the Moon and Mercury. Finally, surface magnetic fields are also capable of focusing and concentrating the incident ion flux in some zones (e.g., peripherally to strong magnetic anomalies); efforts to recover implanted solar wind hydrogen for utilization purposes may therefore be more efficient if they are directed toward these high-flux zones.

Atmospheric measurements

A local array of atmospheric sensors like those used in the global array (Chapter IV) should be deployed. The minimum package is an ion mass spectrometer and a neutral gas mass spectrometer. These should be deployed prior to base construction at the base site and at two sites east or west of the base, one at 20-30 km range and the other at 100-200 km range. This deployment is crucial in monitoring atmospheric contamination caused by establishment and operation of the base. It would be beneficial to place an instrument package 20-30 km north of the base to check the symmetry of the gas flow from the base.

GEOSCIENCE INVESTIGATIONS FROM AN ADVANCED LUNAR BASE

As the lunar base expands and its facilities become more elaborate, geoscience studies will blossom. Greater ranges for astronaut travel will allow substantially more sampling and deployment of closely-spaced geophysical arrays. Most importantly, robotic field geologists teleoperated from the lunar base or the Earth will extend the reach of geologists around the Moon, transforming a single base into a global base.

The roles of humans and robots

As global geologic reconnaissance of the Moon proceeds, we will identify increasingly more detailed and complex problems to study. Such problems will require field and laboratory work; moreover, field geology is a work and time intensive process that requires repeated visits to various sites in conjunction with laboratory analysis. Most importantly, geologic field study requires the guiding presence and synthesis capability of human intelligence and experience; this human presence must be available instantaneously for field work to proceed most efficiently.

Given such a requirement, what techniques are best suited to accomplish these scientific goals? For these complex surface operations, two basic approaches are available: human and teleoperated robotic field geologists (Spudis and Taylor, 1988). The principles of human geologic field work are well understood after 200 years of terrestrial experience and can be applied to the Moon with only minor modifications (Schmitt, 1973; Spudis, 1984).

Teleoperated robots have many potential advantages over humans, including sensory capacities at a variety of wavelengths in the electromagnetic spectrum, great physical strength and endurance, and the ability to work in the harsh lunar environment unencumbered by complex life-support systems. Such machines could be under the direct control of geologists at the lunar base or on the Earth, backed up by science and support teams on the Earth. The robots would make extensive or intensive traverses of selected regions and return samples to the base for preliminary examination and ultimately, return to Earth. A tentative design concept for such a teleoperated robot is shown in Figure VI-6 and Table VI-1. This robot is capable of sophisticated surface operations and possesses sensory abilities specially configured to optimize it for geologic field work. A desirable goal of this type of surface operation is to give the operator the sensation of telepresence (Wilson and MacDonald, 1986). During telepresence, the operator possesses the complete sensory capability of the robot, including three-dimensional vision and the sense of touch, and has the sensation of "being there." This technique of conducting field work from the lunar base may be the most effective way to explore the Moon.

In contrast, human field exploration would probably need extensive machine support anyway and would have to be carefully planned and of limited range

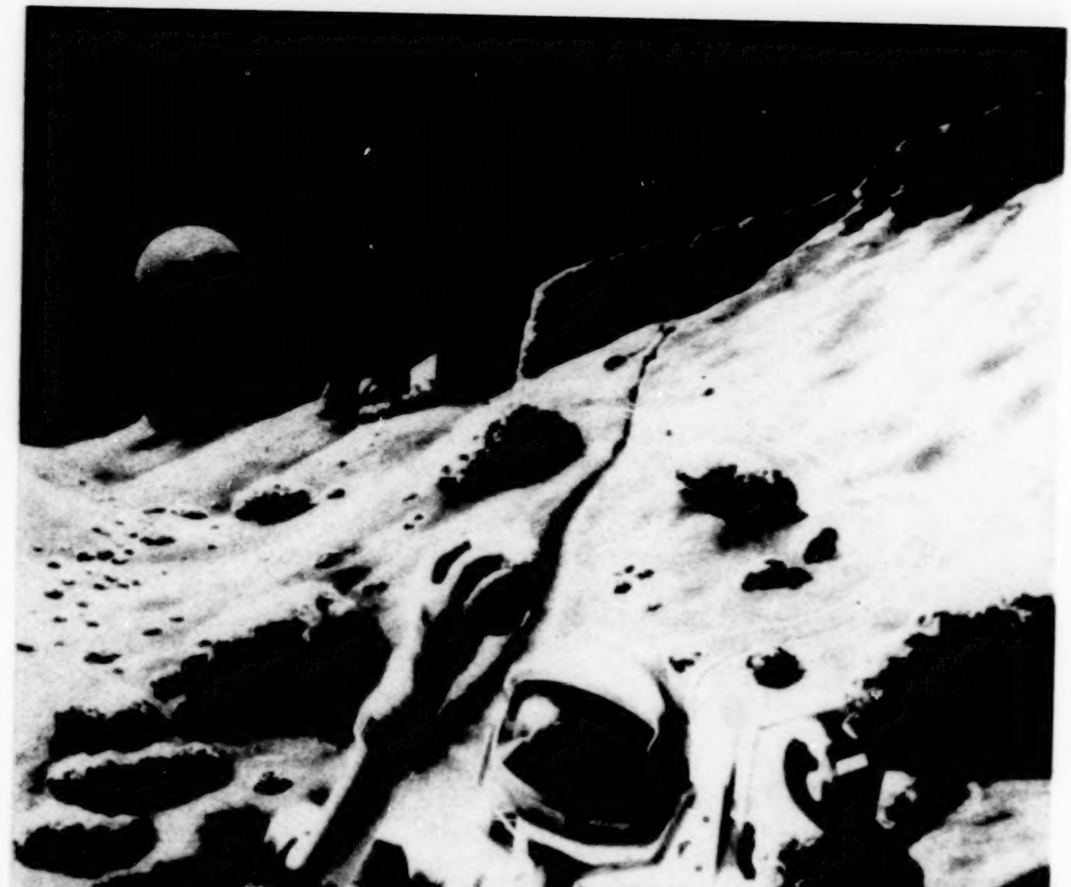


Figure VI-6. Artist's conception of Teleprospector, a teleoperated, robotic field geologist. Its head has two high-definition television cameras so the remote operator can see in stereo. The head can turn and move up and down in response to the operator's head movements, creating a sense of being in the body of the robot. Both hands shown here are dexterous and provide tactile feedback to the operator, adding to the sense of telepresence. One or both hands can be exchanged for sampling tools located behind the torso (note drill symbol). The third eye is a visual-infrared spectrometer to aid in rock identification. As depicted here, the robot communicates with a parent rover, which in turn communicates with the remote operator. NASA painting by Patrick Rawlings.

Table VI-1. SPECIFICATIONS FOR TELEPROSPECTOR, A TELEOPERATED ROBOTIC FIELD GEOLOGIST.

System	Instrument or device	Comments
Mobility	Roving vehicle	Range 1000s km
Vision	Stereo, high-definition color television	Minimum resolving power 30" of arc; telescope mode, 1" of arc
Manipulation	Anthropomorphic arm and hand with tactile feedback	
	Percussion hammer and drill core arm	Capable of extraction of 2-cm diameter rock core
Sample Identification	Visual-infrared mapping mapping spectrometer	0.3 to 20 microns; 1200 spectral channels
	X-ray fluorescence	Real-time chemical analysis
Storage	Four to five sample return containers	Each container with over 200 documented subcompartments

and short duration in order to minimize risks from radiation exposure and possible injury. Human field workers will probably have advantages over remotely-controlled robots in mobility and small-scale dexterity, and in the intangible (but important) sense of direct personal involvement.

A combination of these two techniques for geologic exploration from a lunar base is highly desirable. Initial field operations in the vicinity of the base could involve both human and robotic workers; such work would ensure that the robotic explorers are working effectively and would give valuable experience and confidence in future operations to the human robot controllers. Next, a series of both extended traverses and intensive field work at complex sites could be conducted by the robotic field workers under human control. These operations would constitute the bulk of lunar exploration, with periodic returns of the robots to the base to return samples and receive maintenance. The results of these explorations would be used to plan short follow-up visits by human geologists to sites of exceptional scientific interest or to sites whose complexity exceeds the capability of teleoperations. This exploration strategy makes a single-site base into a "global" lunar base through the use of a central operations center for long robotic traverses without the cost or weight encumbrances of human life-support facilities.

Field studies requiring intensive "human" field work

As the exploration of the Moon progresses, we will undoubtedly encounter scientific problems of such detail and complexity as to require the acquisition of additional data through intensive geologic field work. In contrast to the missions previously described, these studies will require long site visits, intensive work capabilities, and the option to revisit sites repeatedly. The goal of such studies is to understand lunar processes and evolution at appropriate or necessary levels of detail. The key factor that distinguishes this type of study from reconnaissance is the direct guiding influence of human intelligence during the work. As discussed above, this presence may take the form of actual human field geologists working from the lunar base or robotic teleoperations from within the base station; either method proceeds along the same methodological lines.

A list of possible targets for intensive field investigation is shown in Table VI-2. At this level of study, we are asking fundamental questions about basic lunar geologic processes and deciphering the detailed history of selected regions. The mechanics of formation of large craters and basins (sites 31-39) may be addressed by the study of the geology of these structures; such work includes understanding the detailed stratigraphy and structure of the crater targets, the relative amounts of primary and secondary ejecta in the continuous deposits, the nature of the impact melting process, and the enigma of central peak and basin ring formation. In addition, many large craters appear to be our best access to deep-seated plutonic complexes that make up the crust as a whole; lunar igneous processes appear to be on display within the central peaks and walls of such large craters. Basin interiors may yet yield evidence of rocks excavated from the lunar upper mantle; the structural relations of rocks exposed within basin rings may likewise provide constraints on ring origin.

The processes and products of lunar volcanism and tectonism are also best suited for protracted field study (Table VI-2; sites 40-42, 46-49). Field study of vent structures and products, sinuous rilles, and small domes and shields will allow a more complete reconstruction of the epoch of mare flooding. The problems of landform genesis posed by lunar geomorphology may be best addressed through detailed field studies; for example, the problem of wrinkle-ridges has long vexed students of the Moon. Cross sectional exposures of wrinkle ridges occur on the Moon (associated with superposed impact craters or volcanic vents; Table VI-2, sites 40 and 46); such localities would be ideal candidates for field study to understand ridge formation and regional tectonic history.

One of the most exciting capabilities resulting from a lunar base is the ability to examine bizarre and enigmatic features. These areas span the Moon spatially and temporally and are probably hints to the existence of rare processes (sites 43-45) or unknown facets of common ones, such as cratering (sites 50-53). Early reconnaissance by Luna-type spacecraft might solve some of the questions raised by these features, but would probably be most helpful in the planning of later, more advanced field study.

All of the targets listed in Table VI-2 require intensive investigation, but this need not be done on separate traverses. The long geologic traverse described by Cintala et al. (1985) includes at least 29 stops that study a wide range of lunar processes and geologic units (see below). Such a long traverse would take many months to complete but would provide an abundance of information pertinent to fundamental lunar science problems.

Example of a detailed geologic investigation

The establishment of a permanent base on the Moon and the development of robotic field geologists opens up the entire lunar frontier to geologic investigation. Given these capabilities, long exploration traverses can be planned. Cintala et al. (1985) have presented an example of such a traverse. They propose traveling 4000 km across the Imbrium-Procellarum region of the Moon (Fig. VI-7; Table VI-3) and cite three main scientific objectives. First, studies will attempt to understand the formation of multi-ringed basins. Such structures, examples of which are present on all large, solid bodies in the Solar System (Fig. I-1), had a profound effect on the lunar crust. Second, the traverse would allow study of large craters, such as Copernicus, leading to an improved understanding of the mechanisms involved in their formation. Third, many volcanic units would be sampled, representing a wide range in age and chemical composition. Features such as rilles, ridges, domes, dark mantles, dark-halo craters, individual flows, and complexes (such as the Marius Hills) could be studied in the field. Besides these topics, the traverse would also shed light on three other important problems in lunar science. The first is the composition of the lunar crust and how it varies laterally and vertically, which would be clarified by noting how the composition varies along the traverse and by sampling impact melt rocks in the floors of craters. The second is that the traverse would allow study of intrusive rocks in the highlands that are likely to be present as blocks in crater ejecta, walls, and central peaks. This would give important information about how highland rocks relate to each other and how intrusions differentiated. Finally, the sampling of melt sheets of many impact craters along the traverse route would permit us to address the question of cyclicity in the flux of cratering in the Earth-Moon system over the last three billion years; such studies have important implications for the history of life.

Details of the areas along the traverse that would be studied are given by Cintala et al. (1985); we summarize the goals of the field work at each area in Table VI-3. At each stop, detailed investigations will be performed like those described above in our example of the Aristarchus Plateau. These stops are only suggestions; there are many others, and results obtained during the expedition are almost certain to change the route. In addition, the geologist operating the robotic field geologist will undoubtedly observe interesting features between planned stops and should have the option to study them.

Table VI-2. Examples of geologic field sites that require intensive field work with human interaction (after Ryder et al., 1989)

Target	Objectives	Landing Point	Comments
Cratering	Determine details of crater and basin formation. Study central peaks and basin rings to determine origin(s). Study melt volumes, melt sheet homogenization, clast provenance, particle motions during cratering flow. Study walls, terraces, and slump blocks. Investigate continuous deposits; primary and local ejecta fractions as a function of radial range. Reconstruct stratigraphy of target. Investigate absolute ages, shock metamorphism of crater materials. Catalog projectile types and changes with time.	32. Copernicus 10° N, 20° W	KREEP/Mg-suite target; central peaks
		33. Tycho 43° S, 11° W	Gabbronorites in central peak; melt sheet surface
		34. Aristarchus 23° N, 48° W	Gabbro in central peak, high Th; KREEP intrusives?
		35. Aristillus 34° N, 1° E	Mare basalt/KREEP target; ray material spectrally distinct
		36. Apennines/Conon 22° N, 2° E	Excavated through Imbrium ejecta to pl bedrock; KREEP-LKFM transition zone
		37. Eudoxus 44° N, 16° E	Alpes Fm., Imbrium deposits; what is origin of knobby basin deposits?
		38. Montes Pyrenaeus 15° S, 40° E	Nectaris ring and melt sheet; pure anorthosite outcrops
		39. Orientale floor 15° S, 85° W	Melt sheet, mare basalt ponds, and Montes Rook Fm.
		40. South Pole-Aitken basin massifs 25° S, 155° E	Largest basin on Moon, chemically anomalous
Volcanism	Characterization of vent and flow systems. Determine eruption and emplacement styles. Determine chemical differentiation through time. Determine origin of volcanic landforms. Determine details of assimilation in mare magmas; search for mantle xenoliths in basalt flows. Variability of mantle sources in space and time. Investigate possible intrusions and ore bodies.	41. Marius Hills 12° N, 55° W	Central vent volcanoes; sinuous rilles
		42. Hortensius domes 7° S, 28° W	Small basaltic shield volcanoes
		43. Rümker plateau 41° N, 58° W	Similar to Marius Hills but smaller complex
		44. Herigonius rilles 12° S, 36° W	Sinuous rille and vent system atop wrinkle ridge
		45. Aristarchus plateau 24° N, 50° W	Dark mantle; Light plains with high Th content (KREEP basalt?); Schröder's Valley sinuous rille complex
		46. Ina ("D-caldera") 19° N, 5° E	Small collapse feature associated with very young basalt flows
		47. Alphonsus vents 13° S, 2° W	Small cinder cones in floor-fractured crater
		48. Near Lassell 14° S, 10° W	Small cones and mare flows

Target	Objectives	Landing Point	Comments
Highlands	Determine small scale geologic setting of ancient crust, plutonic intrusions, and ancient volcanics. Search for blocks displaying primary igneous layering. Determine composition and origin of anomalous materials. Sample and investigate all plutonic units identified remotely. Determine provenance of lunar meteorites. Characterize cratering process at all scales	49. Silver Spur 25° N, 4° W	Layered materials in Apennines; igneous or sedimentary layering?
		50. Montes Caucasus 32° N, 7° W	Uplifted pI crust in rectilinear fault blocks
		51. Tsiolkovsky peak 20° S, 129° E	Uplifted far side crust in crater central peak
		52. Mons La Hire 28° N, 25° W	Part of Imbrium ring; spectral anomaly
		53. Gruithuisen domes 36° N, 40° W	Rhyolitic domes or basin massifs?
		54. Hansteen Alpha 12° S, 50° W	Spectral anomaly; volcanic or basin massif?
Geologic oddballs	Unusual morphologic features indicate either rare geologic processes or unknown facets of common ones. Determine ages, compositions of units. Determine origin(s) of landforms. Search for exotic processes and materials	55. Struve L 21° N, 76° W	Orientale basin secondary; melt-lined floor?
		56. Donut crater in Humboldt 26° S, 83° E	Concentric crater, possibly a secondary
		57. Crater in Barbier 24° S, 158° E	Volcanic complex or basin secondary crater?
		58. Reiner Gamma 6° N, 59° W	Swirl material, magnetic anomaly; comet impact?
		59. Marginis swirls 15° N, 90° E	Swirl material, magnetic anomaly; comet impact?

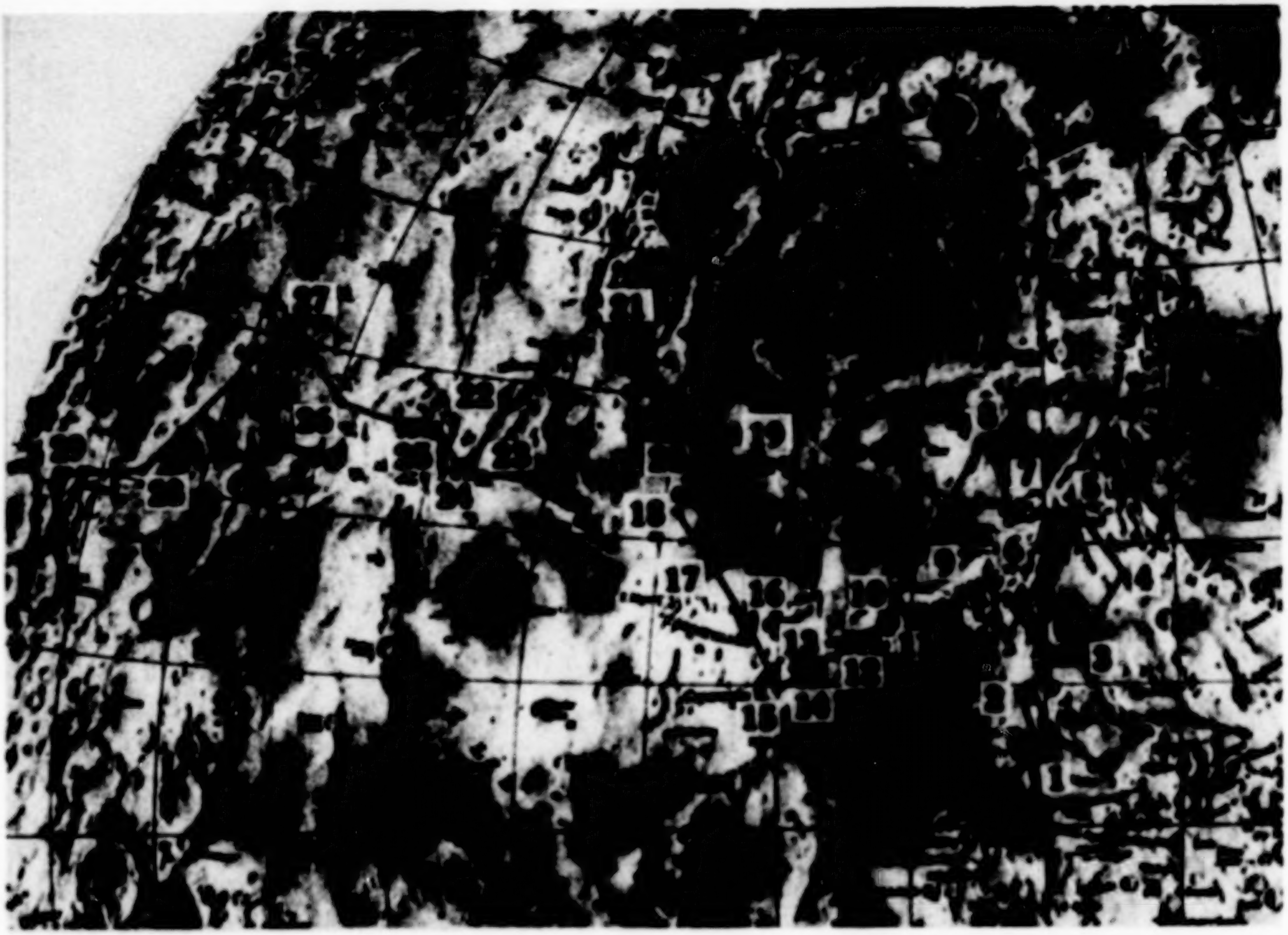


Figure VI-7. The route of a proposed traverse across the Imbrium-Procellarum region is illustrated here on a National Geographic (Lambert equal area) base map. Numbers refer to the prime field sites described in Table VI-3. Although segments are drawn as straight lines, they would actually be sinuous as the crew made numerous shorter stops along the way.

Table VI-3. SITES FOR INTENSIVE STUDY IN THE IMBRIUM-PROCELLARUM REGION OF THE MOON[a].

Stop[b]	Feature	Features to study
1	Murchison Crater floor	Unusual morphology of floor; Fra Mauro and Cayley Formations
2	Fra Mauro Formation	Fra Mauro Formation; possible pyroclastics associated with Rima Bode
3	Mare Vaporum	Mare basalts; geophysics of basin
4	Ina	Possible young caldera
5	Conon Crater	Stratigraphy of Imbrium ejecta
6	Apennine scarp	Stratigraphy of Imbrium ejecta; possible Imbrium impact melt
7	Apennine Bench Formation	Non-mare volcanics
8	Montes Archimedes	Thorium-rich rocks with unusual spectral features
9	Wallace Crater	Relatively young basalts; ray material from Copernicus; geophysics to understand basin stratigraphy
10	Eratosthenes ejecta	Emplacement dynamics and age of Eratosthenes ejecta
11	Eratosthenes interior	Impact melt; geophysics of crater
12	Copernicus Crater rays	Ray materials and local basalts
13	Copernicus continuous ejecta	Crater ejecta and local materials
14	Copernicus rim materials	Ejecta from depth and impact melt; multi-spectral panorama of crater
15	Copernicus central peaks	Deep-seated rocks; impact melt
16	Montes Carpatus	Imbrium and Copernicus ejecta; possible pyroclastics
17	Tobias Mayer Rilles	Volcanic features
18	Euler Crater	Young basalt flows

Table VI-3 continued

19	Mons La Hire	Inner ring of Imbrium basin
20	Eratosthenian flows	Relatively young and chemically-distinct mare basalts
21	Gruithuisen domes	Nonmare volcanic features or Imbrium ring massifs
22	Prinz rilles	Volcanic features
23	Aristarcus crater rim	Ejecta, impact melt, rim stratigraphy and structure
24	Aristarcus Crater floor	Melt sheet, central peaks, geophysical profile
25	Vallis Schroteri	Pyroclastic deposits and basalts
26	Schiaparelli	Young, Ti-rich mare basalts
27	Lichtenberg Crater	Youngest basalts on Moon
28	Struve L Crater	Ejecta from Orientale basin
29	Balboa Crater	Fractured floor

[a] From Cintala et al. (1985).
[b] See Fig. VI-7 for locations of stops.

VII. CURATION AND ANALYTICAL FACILITIES AT A LUNAR BASE

Geologic field work and other sampling activities on the Moon will require that the lunar base be capable of both sample curation and analysis. The thoroughness and technical complexity of these endeavors will increase as the base expands from a spartan scientific outpost to a sophisticated, multipurpose base and, eventually, to a thriving city on the Moon. This chapter outlines curation and analytical facilities necessary at an initial base or outpost and how their capabilities could increase with time.

CURATION

As demonstrated by successful curatorial facilities such as the gargantuan Smithsonian Institution or the modest but high-tech Lunar Curatorial Laboratory at the Johnson Space Center, curation is a multifaceted enterprise. Curators provide samples to scientists, perform preliminary examinations of samples, keep track of the samples and associated information (e.g., where each scientist's sample came from), catalog the specimens and information about their collection, and ensure that the collections are preserved for future study. The curatorial facilities at the lunar base must allow on-site astronaut-curators to perform these services, as well as prevent contamination of the samples, either on the Moon or during transport to Earth.

As a practical matter, curatorial resources at an embryonic base will be substantially less elaborate than those now in use in the Curatorial Facilities at the Johnson Space Center (JSC). A large part of the effort at JSC involves processing samples to fill specific requests from individual investigators. This will not be done on the Moon (at least initially); appropriate samples will be sent to the scientific community back on Earth, where allocations of subsamples will be made. Moreover, another significant part of the JSC effort is devoted towards protecting samples from contamination, which will not be a serious problem at a lunar base, unless the facility is located too close to a habitat and its life-supporting atmosphere. Finally, an early base on the Moon will be severely limited in both personnel and time available for curatorial activities, so procedures will have to be streamlined.

Sample documentation will be an extremely important curatorial activity, one that includes ensuring that information collected at the sampling site, such as electronic imaging and other field observations, is preserved, archived, and associated with the proper sample. This documentation also includes keeping an up-to-date record of the location of samples and subsamples, requiring accurate record keeping, which, in turn, necessitates adequate computing power. Much of the record keeping could be done by Earth-based assistants who would transcribe information dictated by workers on the Moon.

Sample processing will be crucial. Specimens must be taken from samples returned to the Base by astronauts or robotic field geologists (see Chapter VI); these specimens will be used for preliminary examination and study on the Moon. After preliminary examination, other specimens or even an entire sample will have to be packaged for transport to Earth, storage on the Moon, or both. These operations must be done under conditions of minimum contamination. One way to achieve this would be to adopt a dual packaging technique, whereby each sample is split at the sampling site into a large specimen (most of the sample), which will remain in a sealed container until returned to Earth, and a small one to be subjected to preliminary examination at the Base.

Preferably, samples will be processed after return to the base. For minimum contamination, the processing facility ought to be located outside the artificial atmosphere of the base habitats. A relatively simple shed could be constructed for this purpose, equipped with work benches and storage shelves. However, to prevent contamination with local dust, the base curatorial facility will need to have a stabilized floor and dust-free walkways. The facility will also need dusting tools (lunar rocks usually contain dust on their surfaces), tools for chipping and perhaps sawing samples, sample containers, packaging and sealing equipment, and equipment for photographic documentation (probably electronic).

Preliminary examination will be an important activity at the Base. Results of preliminary examinations will be used to plan additional sample collecting activities and to decide whether and how much of a sample is to be sent to Earth for extensive study, studied further on the Moon, or simply stored for future use. Depending on limitations of the analytical facilities at the base and of payload capacities of spacecraft, the policy for transporting samples to Earth might range from "bring them all back" to "bring back subsamples of only the most interesting samples." For limited sample transport capability, preliminary examination will be essential to identify and isolate the most significant samples. Even with liberal sample payloads to Earth, a considerable number of samples will be stored indefinitely on the Moon. Numbered storage containers or bins will be necessary, and the location of each sample will be entered into the curatorial data base to permit easy and accurate recovery. These curatorial requirements necessitate that astronaut time be allocated to curatorial duties. For maximum efficiency, therefore, curatorial operations must be as automated as possible.

ANALYTICAL FACILITIES

The degree of sophistication of analytical facilities at a lunar base requires detailed study. Clearly, all available analytical techniques will eventually be applied to samples collected as part of geological investigations from the base, but which analyses should be done on the Moon and which should be done on Earth? The answer lies in the relative cost of transporting, maintaining, and operating equipment on the Moon versus the cost of transporting samples to Earth. An additional important factor is the time lag involved in sending samples to Earth for analysis because of the need for rapid analysis to help plan the next geological field trip.

The following assumptions strongly color the discussion below: First, at an initial base, the number of people is likely to be small, so analytical facilities should be highly automated or teleoperated from Earth. Labor-intensive sample preparation or analytical procedures should be avoided. Second, we assume that the cost of transporting samples to Earth is likely to be less than that of establishing elaborate analytical laboratories on the Moon. If these assumptions turn out to be incorrect, the strategy outlined here will require modification.

What analyses should be done on the Moon?

There are four primary justifications for performing rock analyses on the Moon. First, it is absolutely essential that properties or quantities likely to be disturbed by transport to Earth or even from the collection site to the base should be measured on the Moon. For example, measurement of solar-wind gases residing in highly mobile sites in the regolith must be measured in situ. The lunar atmosphere must also be measured on the Moon; collection of this tenuous gas and retention of its isotopic and chemical composition during transport to Earth may be impossible.

The second reason for performing analyses on the Moon is to provide rapid data collection in order to support additional sampling and field work. Some field studies may be done at sites so distant from a base that analyses ought to be done in the field during collecting expeditions. The data from such analyses will help plan continued sample collection, reassess local objectives, and evaluate subsequent traverse targets. Some sampling sites, such as those in the vicinity of a base, can be visited repeatedly without difficulty. For such sites, the capability to analyze samples between visits could be of great value in planning additional sampling. Turnaround time for analyses of samples returned to Earth is likely to be limited by the frequency of supply trips, which at first might not be more often than a few times a year. Results of analyses at the Base would probably be available in days or weeks, which is a useful time period for supporting sample collection during a detailed geological investigation.

The third justification for analyzing samples on the Moon is to decide which ones should be sent to Earth for detailed study. Initially, when base personnel are committed mostly to start-up tasks, it might be cost effective simply to return all samples to Earth without screening. However, as operational capabilities at the base increase, it is likely that the cost of performing preliminary examination and screening on the Moon will become less than that of transporting all samples to Earth. Thus, at some stage during the development of the base, a laboratory for preliminary examination of samples will be established.

Finally, as the base becomes progressively more capable, teams of geologists will be exploring the Moon for both science and economics. Because more and more people will be living on the Moon, more science will be done on the Moon, including analyses of rocks and soils.

Analytical facilities at a lunar base

The sophistication of analytical facilities will grow with the base's operational capability. A scheme for how analytical facilities might evolve is summarized in Table VII-1. Start-up facilities will be very basic. They will probably consist of a stereo microscope (probably enhanced by a visual-infrared mapping spectrometer, or VIMS) for rock and mineral identification, and a crude chemical analyzer (e.g., an alpha-backscatter spectrometer, an X-ray fluorescence spectrometer excited by radio-isotopes, or a gamma-ray spectrometer) for quantitative measurement of a few key elements in rock chips. These instruments will permit general classification of the samples and allow a reasonable judgement about which ones to transport to Earth.

At the next level of capability, analytical facilities will probably include an automated device for making polished sample mounts, and a reflected light

Table VII-1. INSTRUMENTATION FOR THREE LEVELS OF ANALYTICAL CAPABILITY AT A LUNAR BASE.

Capability	Instruments	Information	Purpose
Basic	Stereo microscope with VIMS Crude chemical analyzer	Mineral identification Grain size Chemical classification	Classification of rock types
Intermediate	Automatic thin-section machine Reflected light microscope with VIMS Improved chemical analyzer X-ray diffractometer Ferromagnetic resonance spectrometer	Above plus: Texture Bulk composition Soil maturity Magnetic properties	Improved classification Identification of unusual samples Identification of soils rich in gases Study of Moon's magnetic field
Advanced	Above plus: Automated SEM with energy-dispersive X-ray analyzer	Above plus: Mineral composition and zoning Microtextures	Above plus: Even better rock rock classification Identify samples unusual in subtle ways

microscope with a VIMS. This equipment will provide basic petrographic information, including mineralogy and texture. If the microscope has an automated stage, it could be teleoperated from Earth, freeing the geologists on the Moon for other tasks. The facility would probably also include a more sophisticated chemical analyzer, such as an automated X-ray fluorescence system for measuring bulk rock compositions. These instruments will permit more accurate and detailed classification of rock types and better identification of unusual samples than would be possible with the more spartan set of instruments described above. The intermediate facility should also include a ferromagnetic resonance spectrometer for measuring soil maturity, which, when combined with Ti content, allows evaluation of soils for content of solar-wind implanted gases, potential sources of rare, volatile elements. The facility might also include instruments for measuring paleomagnetic properties of samples as there is some concern that the weak magnetization of lunar samples can be contaminated by the Earth's strong field.

With a continued increase in the base's operational capabilities, it would be desirable to add an automated scanning electron microscope with an energy-dispersive X-ray analysis system for performing mineral analyses. Again, this could be an automated instrument teleoperated from Earth. This instrument could provide detailed information on mineral compositions, permitting accurate classification of rock types and, more importantly, permitting identification of samples that are unusual in subtle but important ways.

Lunar base analytical facilities any more sophisticated than those described above are neither practical or necessary for the foreseeable future. For example, it would be highly desirable to obtain geochronological data. However, such data will be much more difficult to obtain on the Moon than basic chemical data because extensive sample processing is generally involved in its acquisition, and complex and sophisticated instrumentation is required to perform isotopic analyses. Thus, until the base becomes a thriving research and industrial community, the cost of establishing facilities to obtain age and isotopic data on the Moon will far outweigh the disadvantages of transporting samples to Earth.

VIII. RELATION OF GEOSCIENCE TO OTHER ACTIVITY ON THE MOON

Geoscience investigations will not be the only activity at a lunar base. Numerous other scientific studies will be conducted, including astronomical observations. As the base expands, mining and manufacturing activities will also expand. Therefore, it is worthwhile to consider how geoscience will affect and be affected by other activities occurring on the Moon.

ASTRONOMY

The Moon is a superb place to situate astronomical observatories (Burns and Mendell, 1988). Its thin atmosphere allows nearly perfect seeing for optical observations and its puny seismicity provides a stable platform on which to construct telescope arrays. The far side is free of radio noise from the natural and artificial sources present on Earth and in low Earth orbit, allowing observations at wavelengths (1 - 10 MHz) not accessible before. The lunar nights are two weeks long, ideal for continuous observations of faint objects. There are drawbacks, such as micrometeorites and a higher radiation level than in low Earth orbit, but the benefits outweigh the problems.

One of the major appeals of the Moon as a location for astronomical observatories is the near absence of an atmosphere and ionosphere. Because almost any activity on the Moon itself will probably increase the density of that atmosphere (e.g., from rocket exhaust), the needs of astronomers may conflict with those of other base users. This is particularly true of mining operations, which might be expected to release substantial amounts of volatiles into the atmosphere. However, many of the science projects listed in this work would require substantial activity on the surface of the Moon, and almost all require takeoffs from and landings on the surface. The seismic effects of other activities on the Moon could affect the performance of astronomical facilities; in particular, any active seismic experiments would have to be carefully coordinated so as not to interfere with astronomical observations.

There are many ways in which the needs of astronomical facilities coincide with those of geoscience. For example, the astronomers' concern about the density of the lunar atmosphere and how it will change with time coincides with the interests of those studying the atmosphere itself; both groups would desire atmospheric monitoring. In addition, if there are astronomical facilities whose usefulness would be compromised by small increases in the density of the atmosphere, an understanding of how the atmosphere responds to anthropogenic additions, both locally and globally, would be essential. This understanding requires missions to start the monitoring process early and modeling of atmosphere dynamics.

Lunar astronomical facilities may be concentrated on the poorly known far side of the Moon, to shield them from the Earth's radiation noise. Detailed mapping will be needed to find a suitable location for observatories, and this mapping could be coupled with geological investigations of the far side. Furthermore, since seismic studies require monitoring stations at points as widely separated as possible, a far-side astronomical facility would be an obvious place to locate a passive seismic station.

Finally, there are some ways in which geoscience can address astronomical questions. For example, the regolith contains a record of 4.5 billion years of interactions with charged particles, including both solar and galactic cosmic rays. Disentangling the record contained in the regolith is our best hope for determining the history of the flux of energetic particles and learning about changes with time in the activity of the sun and the galaxy.

SPACE PLASMA PHYSICS

Plasma and magnetic field sensors on the lunar surface can be used for observations to advance our fundamental understanding of the physics of plasmas in space. These sensors can be part of the sensor networks recommended in Chapter IV for environmental monitoring.

The Moon and asteroids are unique objects in the Solar System with respect to their interaction with the solar wind. All other planetary bodies have thick atmospheres (Venus, Mars, comets) or large-scale magnetic fields (Mercury, Earth, Jupiter) that prevents the solar wind from penetrating to the surface. Because the Moon lacks such shielding, the solar wind and other extralunar plasmas (cosmic rays, magnetospheric plasma) impinge upon the surface directly with only small retardation in regions of localized magnetic fields. The details of the interaction between the solar wind and the Moon are still not fully understood.

During each orbit the Moon spends about 20 days in the solar wind, four days in the magnetosheath (thermalized solar wind plasma), and four days within the magnetospheric plasma sheet. The global environmental array described in Chapter IV will provide a cluster of sensors that can be used to study basic processes that transport and energize plasma in these regions.

The interaction between neutral gases and interplanetary plasma is a fundamental phenomenon that affects our understanding of other problems as diverse as the origin of the Solar System and transient behavior of comets. Although no significant natural gas releases on the surface are expected, human activities associated with the base will provide gas emissions that can serve as valuable space plasma physics experiments. Such gas releases occurred during the Apollo program as a result of Lunar Module landing and liftoff, S-IVB impacts, and venting of the pressurized cabins. Even though these had not been intended to serve as gas releases for experimental purposes and there was only a very limited sensor array on the surface, they provided valuable information.

EARTH SYSTEM SCIENCE

The Moon is an excellent site for terrestrial observations, both of the present Earth and of our planet's intricate past. This unique combination of the Moon as an observation platform and as a recorder of Earth's past ought to be utilized as we try to understand how the Earth works.

Instruments on the Moon can be used to view the land and oceans, the atmosphere, and the outer regions of the ionosphere and magnetosphere. These observations can extend to the polar regions, which are not visible from closer locations, such as equatorial geosynchronous orbit. Unlike satellites at geosynchronous orbit that view only one hemisphere, during the course of one Earth day, a lunar-based observation post will view all locations on Earth (Fig. VIII-1). Systems in low polar orbit view a specific location only once per day for a short period of a few minutes. Filtered imaging systems at a base could monitor phenomena that affect the health of the planet continuously for periods as long as 12 hours each day, such as atmospheric weather systems and polar ice patterns. At higher altitudes the geocorona, the plasmasphere, radiation belts, and magnetosphere can be monitored by lunar-based detectors. The deployment of such imagers of the Earth's space plasma environment was recently ranked by the National Academy of Sciences as a high priority for space research.

The Moon can also be a platform for solar observations. Each month allows 14 days of uninterrupted solar observations from a single site, and if a far side site is also available, continuous observations are possible. Observations of such duration are needed to develop an understanding of the Sun's interior by helioseismology and to develop a predictive capability of solar phenomena (e.g., solar flares and solar cycle variations) that affect the solar-terrestrial system. As noted in Chapter II, the regolith contains up to 4 billion years of the Sun's history. If the ages of specific layers in the regolith can be determined, then isotopic analyses of solar wind gases trapped in soil grains will provide enormous insight into the nature of the Sun at those times. The final result would be an improved understanding of how the solar output varies with time, providing the basis for predictions of its output in the future and for understanding the fossil record of life on Earth.

The millions of craters on the Moon are all potential data points in the search for periodicity of impact flux, which may relate to mass extinctions on Earth. Lunar craters can be dated by several techniques. Ages of a few hundred of them (well within traverse range of even a start-up base) would establish if the impact rate changes periodically and, if so, whether the peaks of increased flux correspond to periods of mass extinctions on Earth. This study would shed light on the history of life on Earth and revolutionize our knowledge of external threats to the habitability of planet Earth in a manner analogous to the way ice cores from Greenland have revolutionized our understanding of climatic variations.

Geoscience on the Moon will also shed light on fundamental problems in Earth's history. For example, volcanic glass deposits on the Moon may contain information about the origin of Earth's atmosphere. These volatile-rich glasses might contain indigenous noble gases that were trapped in the Moon when it formed, rather than being added by the solar wind. All that is known with certainty about indigenous lunar noble gases is that they are rare--no more abundant than typical terrestrial contamination levels--in the Apollo samples analyzed to date. Indigenous noble gases are potentially important for deciphering the history of volatiles in the solar nebula and on Earth. Noble gases in the terrestrial atmosphere differ both elementally and isotopically from any other known Solar System reservoir. The noble gas patterns most similar to Earth's are those of the martian atmosphere, but this could be because of either similar planetary processes or to the proximity of the two planets in the solar nebula. The composition of indigenous noble gases in the Moon, particularly compared to those of Earth, could constrain the location and timing of some of the processes that led to the present terrestrial atmosphere.

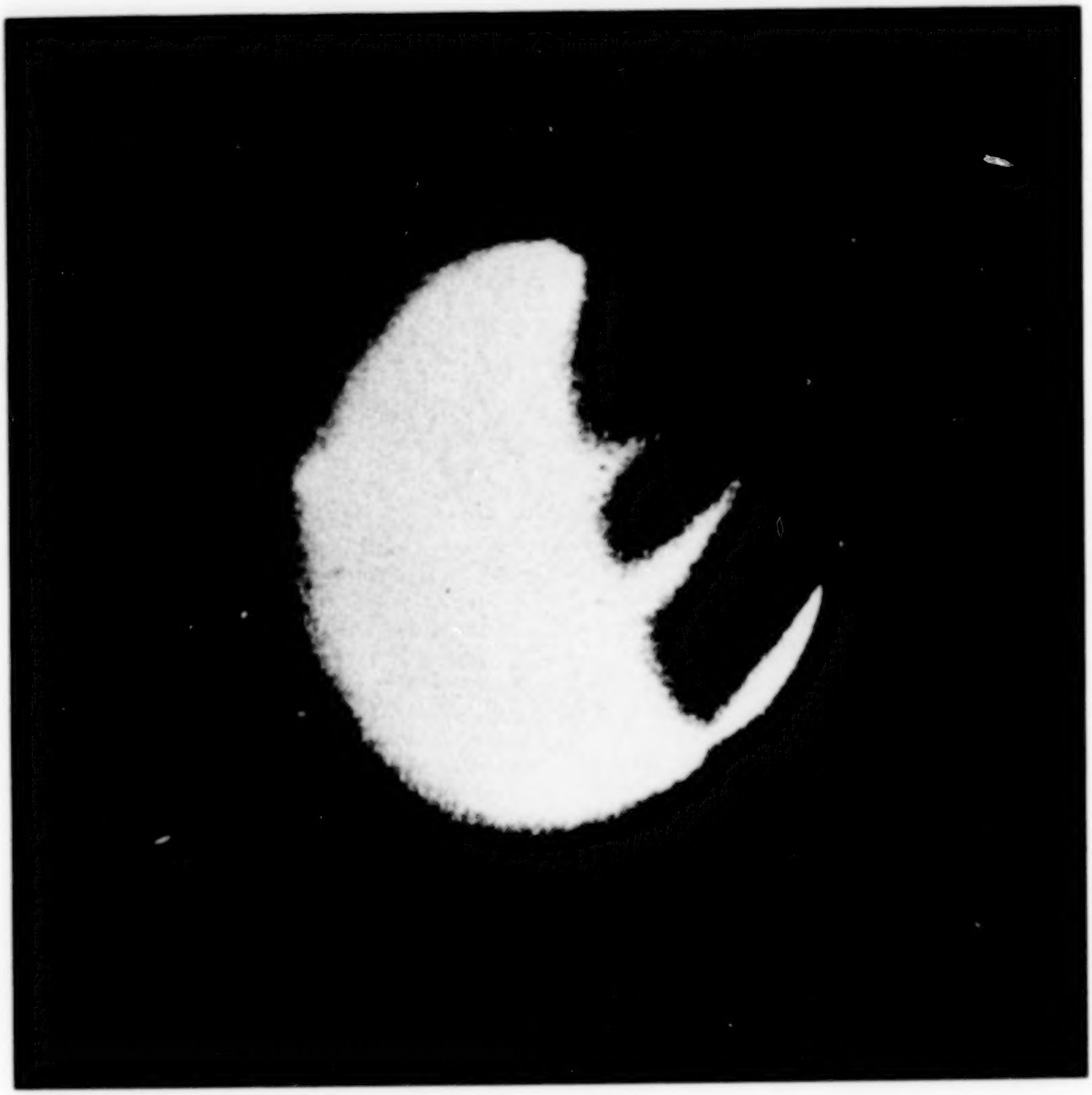


Figure VIII-1. An ultraviolet image of Earth's dayglow from the sunlit atmosphere, the polar auroras, and the nighttime airglow in tropical regions. It was made by an ultraviolet camera/spectrograph operated on the lunar surface during the Apollo 16 mission in 1972. Such synopic observations of the entire Earth and the particles and fields surrounding it will be possible from a lunar base.

LUNAR MINING AND RESOURCE UTILIZATION

An important aspect of lunar mining will be prospecting, whether for specific common minerals (e.g., ilmenite), solar wind-implanted species (H, He, C, N, O), polar ice, or more exotic ores that are not presently known to exist on the Moon. Such prospecting will provide information for and require information from studies of the composition of the Moon's surface. Once potential mining facility sites are found, detailed knowledge of the depth and structure of the regolith at those sites will be desired, presumably requiring on-site study. Thus, both prospecting and geology are likely to involve detailed mapping. In addition, geophysical monitoring stations can be set up during prospecting forays.

Mining itself may have less in common with science objectives. Most of the proposed mining techniques (see Haskin, 1985) involve utilization of surface or near-surface material. However, every trench that is dug provides a potential site for study of the variations of the regolith with depth, just as every terrestrial roadcut contains a wealth of information about the history of the Earth's surface at that location. The tailings from mining operations would also provide an abundant source of local material at a mine site for studies which do not require detailed information about the material's pre-excavation location.

Any digging beyond the regolith will provide geologically useful detail on the strength, structure and composition of the bedrock. If explosives are needed for excavation, they could produce a signal source for an active seismic experiment.

The most significant conflict between mining and science is likely to be in the area of atmospheric modification. Most resource utilization schemes are likely to involve a substantial addition of volatiles to the lunar atmosphere, altering the nature of the atmosphere itself and, potentially, the surfaces on which atmospheric and solar wind species are implanted. In addition, mining activities will result in significant numbers of low-level seismic signals. Decisions on where to locate seismic networks will have to include the consideration of whether such activity can be used as part of active experiments, or whether networks will have to be located far away from mining activities.

LUNAR BASE LOCATION AND CONSTRUCTION

Several questions of fundamental importance in deciding how and where to construct a lunar base are also scientifically interesting in their own right. For example, decisions on shielding will have to be based on a better knowledge of the variations in the flux of neutrons and ionizing radiation at depth in the regolith. This knowledge is also of interest to those who model cosmic-ray interactions with matter and those who use cosmogenic nuclides to determine chronology. Similarly, if there is water stored at the poles, it might make a polar base a more attractive option, while its presence or absence could be used to constrain models of volatile transport in the atmosphere.

Lunar base construction will require heavy equipment. Some of this equipment could be used later for geological investigations. For example, earth-moving equipment could be used for trenching operations to study the regolith.

LAUNCH/LANDING OPERATIONS

Every rocket launch and landing will inject significant amounts of material into the atmosphere. For example, each Apollo mission temporarily doubled the density of the lunar atmosphere. Again, this will make it more difficult to study the composition of the indigenous atmosphere, and could pose problems for astronomers. However, it has some benefits for the study of atmospheric processes. If atmospheric monitors (mass spectrometers) are in place, each launch or landing can then be used to study lateral mixing of the atmosphere as well as the processes that remove material from the atmosphere.

Each launch from the Moon to Earth or to low-Earth orbit will also provide an opportunity to return samples for detailed investigation. Large payloads are not necessarily required. Since many modern analytical techniques for analyzing elemental or isotopic compositions require milligrams of sample or less, if some preliminary examination can be done on the surface, even a few grams of well-chosen samples could answer many scientific questions.

IX. SCENARIOS FOR LUNAR GEOSCIENCE EXPLORATION

Experience in the geological exploration of the Moon and planets, including two centuries of intensive study of the Earth, allows us to develop a logical and comprehensive plan to continue the geoscientific exploration of the Moon. The plan presented here is both scientifically rigorous and operationally flexible. Four kinds of geoscience research activities are described: orbiting spacecraft, global geophysical networks, reconnaissance missions with automated spacecraft that return samples to Earth, and field investigations. Only field investigations require the infrastructure provided by a permanently-staffed lunar base. A sample time line for these activities and supporting technology development appears in Fig. IX-1.

Orbiting spacecraft

It is absolutely essential that the entire lunar surface be mapped geochemically, mineralogically, geophysically, and photographically. As explained in Chapter IV, this requires a spacecraft or series of them to be placed in polar orbit. The proposed Lunar Observer mission would fulfill most of the pressing scientific requirements; this mission should include a subsatellite for measurements requiring two spacecraft in orbit simultaneously. Examples of such measurements are electromagnetic sounding of the interior and mapping the far side gravity field.

A lunar polar orbiting mission is the essential next step in the exploration of the Moon. It will provide critical information about where to locate a base, regions containing potential resources, sites for reconnaissance missions and intensive field work, and placement of the stations of a geophysical network.

Once global maps have been obtained, other orbital missions could be planned. One cannot predict the types of measurements they would make until the global maps are in hand, but several possibilities exist. For example, high-resolution geophysical measurements might be valuable in unraveling regional structures or in evaluating resources. These might employ tethers to lower instruments close to the surface, thereby leading to increased spatial resolution. Follow-on orbital missions need not precede establishment of a base, although some high-resolution images of contiguous areas may be needed before the base is constructed.

Installation of a global geophysical network

As described in Chapter V, a thorough understanding of the Moon is impossible without knowledge of its interior. This requires the installation of a geophysical network of at least eight stations. Each station must include a seismometer, heat-flow probe, and atmospheric sensors. Deployment can be by automated landers or rovers, penetrators, or astronauts (see Chapter V for a discussion of these options). Establishment of the network need not take place before the base is established, although it would be desirable to begin as soon as possible and continue to deploy stations during the lunar base era. The value of the global network will be enhanced by the improved understanding of local and regional crustal structure that will come with detailed geophysical studies from a base on the Moon.

Automated sample-return missions

Many significant scientific questions can be answered by study of samples returned by relatively unsophisticated, automated spacecraft, as detailed in Chapter V and in Ryder et al. (1989). Landers similar to Soviet Luna spacecraft could be sent to numerous sites over a period of many years, starting before a base is established and continuing long afterwards. In fact, such sample-return missions are an important part of the general scientific exploration of the Moon and may or may not be related to a lunar base program. Development of the technology to collect samples from specific locations will offer a cost-effective technique to sample other planetary surfaces as well.

Field work

Geological field work requires long-duration missions (Chapter VI), so it clearly requires the capabilities that will accompany a lunar base. These capabilities will expand with time. Prior to Base establishment, autonomous or semiautonomous rovers ought to be tested. These will be essential ingredients in the detailed exploration of the Moon and could provide a test of the concept of a robotic field geologist (Chapter VI). Initial human field work might be restricted to within 10 to 20 km of the Base site. This could be expanded by development of pressurized roving vehicles to perhaps 100 km, but giant leaps will come with the development of robotic field geologists, which will have global range. As the Base is being constructed, astronaut time will be devoted to construction, near-base field work, deployment of geophysical equipment, and other experiments, but once this phase of activity is completed, the technology for the teleoperated field geologist needs to be ready. We

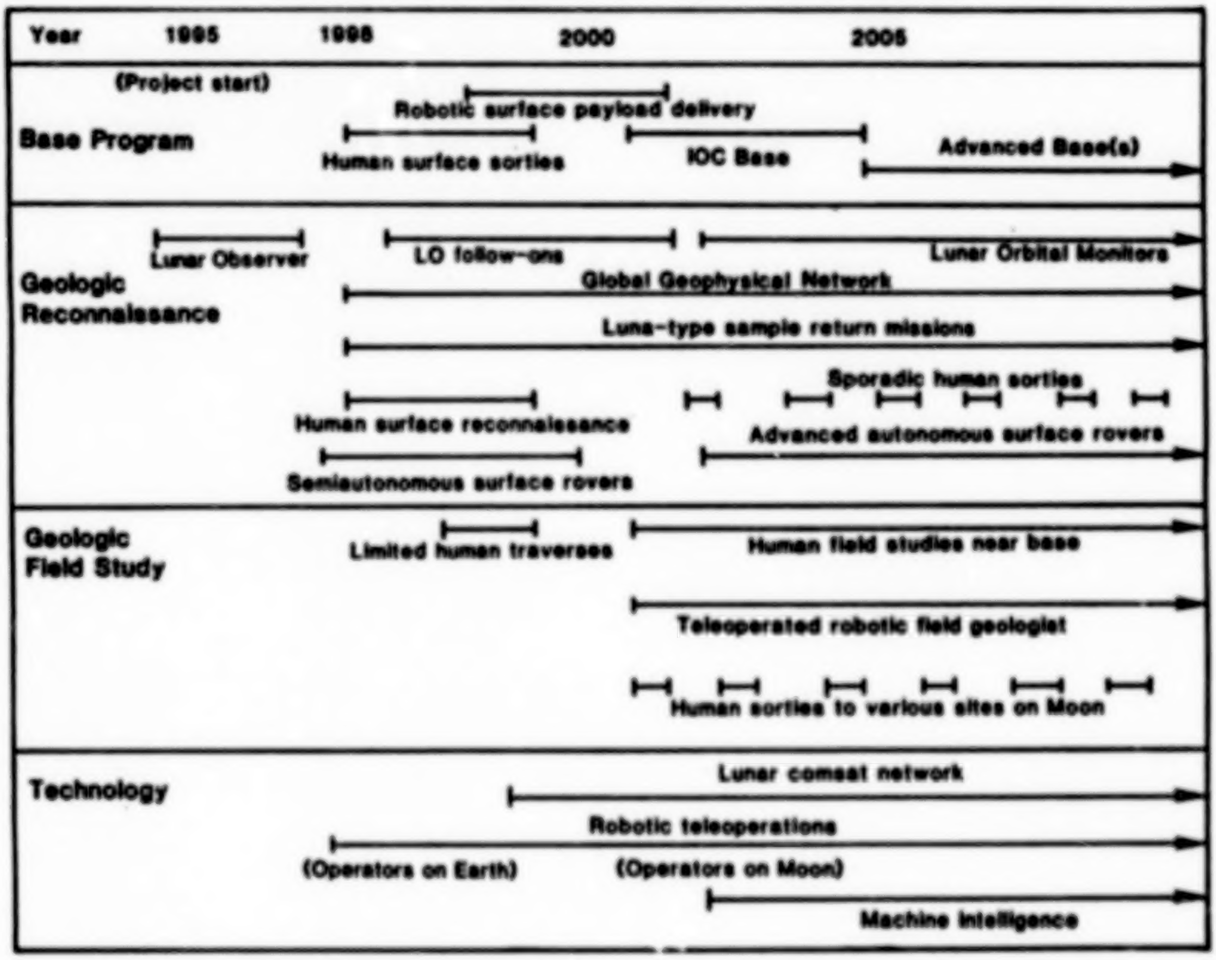

Lunar Base: Geological Requirements in Relation to Other Milestones

Figure IX-1. Proposed time-line for lunar geoscience exploration.

estimate that robotic field work could begin about a year after the base is founded.

Summary

The long-ranged plan described above is flexible. Except for the immediate need for a polar-orbiter mission to map the Moon, the timing of other types of investigations is open. Reconnaissance and network science can begin before or after a base is established, or even if a base is not established. Both must continue for years after the base is operational. Field work can begin modestly near the base, but then can take place anywhere on the Moon using pressurized roving vehicles carrying human geologists and robotic field geologists.

X. TECHNOLOGIES REQUIRED FOR LUNAR GEOSCIENCE INVESTIGATIONS

The scientific investigations described in this report require that new technologies and capabilities be developed. These are outlined below and include technologies that will be required for automated missions and those needed to support human exploration.

General technology requirements

All equipment used in the scientific exploration of the Moon must be capable of working for many years in the lunar environment. It must withstand the radiation at the surface (UV light, solar flares, and cosmic rays), the hard vacuum, micrometeorite flux, thermal variations, and ubiquitous dust. The lack of a lubricating atmosphere will result in substantial wear on moving parts. These environmental factors must be considered when designing scientific instruments, equipment, and facilities. In addition, the following general factors will be important technology considerations (adapted from Johnson and Wetzel, 1989): 1) Automation, telepresence, and robotics for construction, operations, and maintenance. 2) Realistic interaction between humans and semi-autonomous robots. 3) Techniques for data gathering, storage, processing, and transmission. 4) Communications and navigation satellite systems (e.g., satellites located at L4 and L5, or a constellation of communication and positioning satellites in lunar orbit). 5) Thermal control systems. 6) Power sources, both at a base and at remote installations. 7) Surface mobility. 8) Earth-Moon transportation systems.

Geophysical instruments

For the most part, Apollo instruments performed admirably. Nevertheless, advances in materials and electronics ought to allow us to design even better ones in the future. It is especially important to improve atmospheric monitors as some of these did not operate during lunar daylight. As discussed in Chapter IV, there are several options for deploying geophysical instruments, including soft landers, penetrators, and humans. To understand which will be most effective, or under what circumstances each is most effective, research must be done on power sources (which must last at least ten years for seismometers and atmosphere analyzers) and on techniques for orienting three-axis seismometers automatically.

Specialized geophysical equipment must be developed for use in the vicinity of a base. A key one will be a seismic survey system consisting of a cable to which geophone are connected. The cable could be played out off a spool on a rover, with connections for geophones every 100 meters. Connectors must be simple (so that suited astronauts can make them) and designed to overcome the problem of ubiquitous dust. A survey system must also be developed so the geophones can be located precisely. In addition, a convenient and safe source of seismic energy must be designed. On Earth, seismic surveys usually employ thumpers, which are heavy plates driven onto the ground. This may be impractical on the Moon, partly because of the lower gravity and partly because of signal scattering in the upper few tens of meters of the surface. It may be necessary to set off explosive charges; how these should be deployed should be studied.

Penetrators

The use of penetrators might be a cost-effective way to deploy geophysical networks on the Moon and other planetary bodies. Penetrators and their instrument payload must be capable of surviving landing at lunar orbital velocity, 1.5 km/sec. Special miniaturized power supplies will need to be developed.

Automatic soft landers

Another way to deploy scientific instruments on the Moon is to use soft landers like the Surveyor and Luna spacecraft. Such spacecraft can also be used to obtain samples (see below). These spacecraft must be as automated as possible so that instruments can be deployed with minimal human interaction. They must be equipped with drilling devices to emplace heat-flow probes and manipulator arms to place seismometers firmly in the ground. Each spacecraft must also contain navigation equipment to land near a designated site and to determine exactly where it landed. It must also be able to transmit data back to Earth from any location on the surface.

Sample collection by automated spacecraft is an important technique for geological reconnaissance. Consequently, some soft landers should contain a stage capable of returning to Earth a few kilograms of material. This requires an array of equipment for launch and navigation in route to a rendezvous in lunar orbit, return to Earth orbit (in which case aerobraking will be needed), or direct return to Earth's surface (thus requiring robust heat shields).

The lander must also be equipped with sampling devices for collecting bulk regolith, core samples a few meters in length, and rake samples (see Chapter V). Coring solid rock will not be required on automated reconnaissance missions.

Tethers

There are interesting possibilities involving the use of tethers from lunar orbit. They could be used to lower remote sensing instruments close to the surface in order to obtain high spatial resolution. Technology issues include communication between the instruments and the orbiting spacecraft, all aspects of the tether, and methods for precision control of the orbit (to prevent the instruments from crashing into mountain peaks).

Automated Roving Vehicles

Geophysical equipment can be emplaced by roving vehicles. These must have ranges of thousands of kilometers. The rovers might need storage capacities large enough to deploy several geophysical stations along a traverse. Rovers could be teleoperated from Earth or a lunar base, with significant autonomy, such as hazard avoidance, built in. Precise navigation is needed but, most importantly, they must be rugged enough to traverse thousands of kilometers of rugged terrain without need of repair. Consequently, important technology issues concerning wheel design, materials, power, and electronics are associated with rover design.

Rovers are necessary to support human geologic exploration. Three main types of rovers can be envisaged. One type must be capable of transporting teleoperated, robotic field geologists over great distances. This rover might be similar to that used to deploy geophysical equipment. It must have extremely long range (thousands of kilometers) and be integrated with the systems on the robotic field geologist. It would serve as the robot's communications link with the operator at the base. A second type of rover would be used to transport astronauts near the base. A vehicle similar to that used by Apollo, but with a longer lifetime, would be adequate. Finally, a pressurized roving vehicle to carry a crew a significant distance from a base will be needed to make regional geological and geophysical studies. Such a vehicle would be a complicated one that contains life support equipment, in addition to navigation and communications systems. It could also contain analytical facilities to aid in sample selection.

Sampling devices

An array of sample-collection tools must be developed. These range from simple scoops, hammers, and rakes to powered devices such as drill cores. Even simple devices are complex when used by automated samplers such as a Luna-type soft lander or a robotic field geologist. Three types of coring tools will be needed: One type would collect small (5-10 cm), oriented cores in solid rock. This device will be used by both human and robotic astronauts. A second type of coring apparatus would be used to obtain deep (2-10 meters) cores in the regolith. This could be used by automated sample-return spacecraft or by astronauts. The third type of coring equipment would be used to obtain very deep (up to 1 km) drill cores. This will be a challenging operation in the anhydrous environment of the Moon and erosion of drill bits will be significant. Finally, geological exploration will make good use of any type of regolith-moving equipment. For example, an important scientific endeavor will be to dig trenches in the regolith down to bedrock. Such equipment will, of course, be developed to construct habitats and to mine regolith.

Analytical facilities

A number of analytical instruments will be required in lunar geologic exploration. They will be carried by astronauts, automated spacecraft and rovers, and robotic field geologists to aid in sample selection. Other facilities will be located at the base (Table VII-1). The first step in developing this technology is to define the optimum mix of equipment for sampling under different conditions and for in situ analyses without sample returns.

Robotic field geologist

Development of a teleoperated robotic field geologist is essential to optimize the geologic exploration of the Moon, giving us global access for field work. One geologist at the base will be able to do field work anywhere on the Moon by projecting himself or herself into the robot. Development of the robot requires continued research on telepresence (including eyesight and tactile feedback), mobility, communications, navigation, all electronic subsystems, sampling tools, and power source. Sensory capabilities need to be developed, especially multispectral imaging and devices for chemical analysis, such as gamma-ray spectrometry. Other important issues include the distance the robot can travel from its parent rover.

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16. Abstract
This document represents the proceedings of the Workshop on Geoscience from a Lunar Base held August 25-26, 1988, at the Lunar and Planetary Institute in Houston, Texas. It describes a comprehensive plan for the geologic exploration of the Moon. The document begins by explaining the scientific importance of studying the Moon and outlines the many unsolved problems in lunar science. Subsequent chapters detail different, complementary approaches to geologic studies: global surveys, including orbiting spacecraft such as Lunar Observer and installation of a global geophysical network; reconnaissance sample return mission, by either automated rovers or landers, or by piloted forays; detailed field studies, which involve astronauts and teleoperated robotic field geologists. The document then develops a flexible scenario for exploration and sketches the technological developments needed to carry out the exploration scenario.

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